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GAMMA RAY ASTRONOMY

W. L. Kraushaar
Department of Physics
University of Wisconsin

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The marvelous unfolding of the large scale and even detailed features of the astronomical universe around us has always seemed to me the finest example of scientific detective work. The astronomer, unlike his physicist, chemist and biologist colleagues is necessarily forced to observe, not experiment. He cannot put the stuff he wants to learn about on a tidy laboratory table and probe it, change it or control its environment. Imagine the handicap and discomfort of any experimental scientist were he restricted to walk about the earth and only observe, promising always to keep his hands in his pockets. To be sure, astronomers are totally dependent upon laboratory sciences, particularly physics, in reaching an understanding of what they see. But their objects of interest are, of course, totally unavailable for experimentation.

Astronomical knowledge seems all the more impressive when one realizes that until the last decade or so, observations were limited to the optical or visible region — a tiny portion of the electromagnetic spectrum. Then about twenty years ago radio astronomy emerged as a new tool — a new window for astronomical studies. The impact on astronomical understanding has been very great indeed. Our own galaxy, the Milky Way, is a radio source, though not a very spectacular one. The total emitted radio power is only 10^{-6} or so of the total emitted light output. Other galaxies which at first glance appear similar to ours emit more radio power than light power. Some objects within our galaxy, notably the Crab Nebula and Casseopeia

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A are very strong radio emitters and are apparently the remnants of super novae or stars which exploded thousands of years ago as a part of their evolutionary process. The very core or center of our galaxy is a strong radio source of unknown nature. It is called Saggitarius A. Pulsars – radio sources within our galaxy that emit their radio power at regularly spaced intervals of time and Quasars – radio sources of very small angular size at supposedly very large distances from our Galaxy are both recent new discoveries of radio astronomy.

Except for the optical region, parts of the infra-red region and the radio region of the electromagnetic spectrum, the earth's atmosphere is essentially opaque. Specifically, beginning with light in the ultra-violet region (3000Å) and continuing on down in wavelength through the x-ray (500 to 0.5Å) and gamma ray (shorter than 0.5Å) regions, direct measurement of cosmic electromagnetic radiation from the surface of the earth is impossible. See Figure 1. Later in the article I shall describe some very ingenious methods of indirect measurement which are useful at exceedingly high energies (or equivalently, at exceedingly small wavelengths). Generally, then, x-ray and gamma ray measurements must be carried out with observing equipment carried up and over the earth's atmosphere, and this is the reason that astronomy in these wavelength regions has only come into being with the availability of high altitude balloons, satellites and sounding rockets.

The discovery of strong cosmic x-ray sources has been one of the truly surprising results of space age astronomy. To date some 30 remote sources have been found and in no case is there yet a good understanding of the physical conditions under which these x-rays are emitted. The relative intensities of x-rays of different energies gives some hint of the emission mechanisms, but certainly no one is yet in a position to predict with certainty the objects in the sky which will be strong x-ray emitters. In view of this, it is not hard to see why, in the early days of space astronomy, x-ray investigations of remote objects were not particularly high on most people's lists of promising things to do with instruments above the atmosphere. The discovery of x-ray emitters was therefore truly a discovery. It was unexpected.

Even before the discovery of cosmic x-rays, several attempts had been made to locate cosmic gamma ray sources. The reason was that there were good reasons to expect that many known celestial objects would emit gamma rays. Radio, infra-red, light, x-rays and gamma rays are all really the same phenomena, of course. They are all electromagnetic radiation and what distinguishes one from the other is the wavelength or energy of the photons. The energy of a gamma ray photon is by definition large. In the early 1950's it had become fairly clear that the mechanism responsible for the emission of radio waves from the strongest cosmic radio sources involved very high energy electrons. This mechanism, called synchrotron radiation because it was in the electron synchrotron accelerators that the process first attracted wide attention, is simply the process by which electrons radiate when in a magnetic field. Given the frequency of the detected radio noise and the approximate intensity of the magnetic fields, it is simple to conclude that the responsible electrons must have rather large energies — energies in the region of tenths of billions to tens of billions of electron volts (1 billion eV = 1BeV = 1000MeV). The presence of these high energy electrons suggested, in fact practically demanded on theoretical grounds, that protons of similar energy should be present in even larger numbers than the electrons. High energy protons, when they collide with the nuclei of atoms, are known to create high energy unstable particles of various sorts. One of the unitable particles is called a neutral pi meson. It carries no electrical charge and decays almost immediately after its creation into high energy gamma rays. Further, high energy electrons themselves, when they collide with the nuclei of atoms, are known to emit or radiate gamma rays of energy comparable to, but of course always somewhat less than, their own. There was thus a fairly direct implication. Radio sources that emit via the synchrotron process should be emitters of high energy gamma rays. Quantitative arguments showed that the relative intensities of the radio noise and gamma rays from a particular source should tell us much about the magnetic field and amount of gas within that source. Gamma rays from these mechanisms should be most easily detected in the region above 50 MeV. The same processes should be operative on up the energy scale to and through the tens of BeV region though the number of high energy gamma rays falls off rapidly with increasing gamma ray energy.

Another and possibly even more exciting type of gamma ray emission has its origin in nucleogenesis — the astrophysical building up the nuclei of the atomic table. It is known with virtual certainty that nucleogenesis occurs in normal stars. Fusion, the combining of light nuclei to form heavier nuclei is in fact responsible for the enormous energy generation within stars. It is also virtually certain, however, that not all the nucleogenesis that must have occurred someplace, sometime, in order to account for the observed relative abundances of the elements, has occurred within normal stars. Perhaps this additional nucleogenesis proceeds more or less continuously as stars pass through their exploding or supernova stage. Or perhaps it occurs within the suspected (but by no means established) super-massive stars. Or perhaps it occurred in some very early stage of the universe in the often-postulated "big bang" explosion.

Newly formed elements have amongst their members instable isotopes or radioactive elements. Some of these isotopes are very unstable and decay into stable isotopes almost immediately. Others live hundreds or thousands of years or even more. When unstable elements decay, they sometimes emit gamma rays, and the energy of the gamma rays for a given unstable isotope is unique so that they provide a kind of signature. The Radium isotope of mass number 226 (Ra^{226}), for example, has a half-life of 1620 years and the gamma ray emitted has an energy of 0.187 MeV.

Pb^{214}, on the other hand, has a half-life of 26.8 minutes and emits gamma rays of 0.352, 0.295, 0.24 and 0.18 MeV. The detection of gamma rays of particular energies, then, would supply unique and very revealing information about where and when their parent elements were created.

While low energy gamma rays of particular and unique energies are emitted by unstable and decaying radioactive isotopes, there is one more process that is effective in producing gamma rays and x-rays, too, over a very broad band of energies. This process is called the inverse Compton effect, and like many astrophysical phenomena, is on a firm theoretical foundation but is practically unknown in laboratory experience. Conceptually, the process is easy to understand by analogy. Imagine that you, an observer at rest, produce somehow a musical note that bounces off of a stationary object. The frequency of the echo will be the same as the frequency you produce. But now suppose the reflecting object is moving at high speed towards you. Another observer on the moving reflector will hear your musical tone increased(the Doppler shift) in frequency by some factor k. But then when the tone gets back to you, the frequency will be increased again(another Doppler shift) by this factor k so that the reflected echo will now have a frequency k^2 times as big as the emitted frequency.

Essentially this same phenomena occurs when low energy light or radio waves bounce from or are scattered by very fast moving electrons. Photon energy is proportional to frequency and the correct factor k, in this case, is E/mc^2 where E is the energy of the electron and mc^2 is the rest mass-energy of the electron. We have seen that electrons of energy 100 to 10,000 MeV must be rather common in radio-emitting objects. Since $mc^2 = 0.512$ MeV, our factor k^2 is in the general region of 10^5 to 10^9. The average energy of the photons of visible light is about 2 eV, and recent measurements in the microwave-near infra-red region show that there is a very large number of photons presumably throughout the universe in the region of

0.001 eV. Scattering or echoing of these optical and radio photons from the very energetic electrons, then, is effective in creating x and gamma rays from 100 eV all the way to 10^9 eV or 1 BeV.

These, then, are the basic mechanisms by which cosmic gamma rays are produced. In summary, we have (a) gamma rays of particular and unique energies in the one MeV region from the decay of radio-active nuclei. Likely sites are super novae, super novae remnants and the very centers of galaxies where unusually massive objects may be situated. (b) Gamma rays of continuous energy distribution from 10 MeV and up produced by high energy protons in their collisions with gas atoms. (c) Gamma rays of continuous energy distribution from a few Mev and up produced by high energy electrons in their collisions with gas atoms. (d) Gamma rays of essentially all energies, including x-ray energies, produced by high energy electrons in their collisions with photons of the light from stars and photons of short wave-length radio or infrared radiation. Likely regions for b, c, and d are wherever synchrotron-produced radio noise emanates.

Detection of cosmic gamma rays is difficult. All the schemes and detection methods that we shall discuss involve ultimately the detection of charged particles, for gamma rays themselves are not directly detectable by any known means. Low energy gamma rays and x-rays are most easily absorbed (and therefore detected) by the photoelectric effect. The gamma or x-ray ejects one of the inner-most electrons of an atom. The ejected electron carries off part of the gamma ray energy — the rest resides within the disturbed or excited state of the struck atom. Ultimately and within a very short time the energy of the struck atom is also converted into electron energy. High speed electrons now have all the energy that the incoming gamma ray had, but their directions bear no relation to the gamma rays' original direction.

At small gamma ray energies, Compton scattering is also a significant absorption mechanism. Here the gamma ray interaction is with one of the outer or loosely bound atomic electrons. The gamma ray is scattered and looses some energy which is given to the electron. The scattered gamma ray may be absorbed and its energy given to electrons just as was the case with the original incoming gamma ray. For gamma ray energies larger than 1.02 MeV(twice the rest mass-energy of a single electron) electron-positron or pair production becomes an energetically possible and important gamma ray interaction. The rest mass-energy of the pair plus their kinetic energy is equal to the energy of the gamma ray. The positron member of the pair will be eventually captured and will annihilate with an electron. In this process, gamma rays will be produced whose energy totals the rest-mass energy of an electron positron pair. These gamma rays will then be absorbed by one or more of the processes previously discussed, and their energy will eventually be transferred to electrons.

We see then, that it is possible through any of these mechanisms that the total energy of the incident gamma ray be converted into high speed secondary electrons. These secondary electrons and their kinetic energy is detectable. In a scintillation counter, for example, the electrons will collide repeatedly with the atoms that make up the scintillation material. Scintillating materials in current popular use are sodium iodide, cesium iodide and a specially prepared transparent plastic. All have the common property that part of the energy lost in them by fast moving charged particles is emitted as light. The light is picked up by a nearby photomultiplier tube and electrical pulses are produced whose magnitude is proportional to the energy of the gamma ray. The energy resolution is limited by the finite number of light photons that are produced. In sodium iodide one photon is emitted for about every 50 eV of electron energy dissipated. But since photocathodes of photomultiplier tubes are rarely more than 20% efficient, the equivalent energy per photoelectron is about 300 eV. Hence when 0.03 MeV gamma rays are detected there are only N = 100 photoelectrons and the energy resolution is about $1/\sqrt{N}$ or 10%.

The first successful cosmic gamma ray measurements in the MeV region were those of Metzger et al, carried on the Ranger space vehicles (1, 2). The instruments were rather simple cesium iodide scintillation counters as are shown schematically in Fig. 2. The cesium iodide is surrounded by a plastic scintillation counter. The time during which the scintillation light is emitted from cesium iodide ($\sim$1 μsec) is much longer than the corresponding time for plastic scintillator ($\sim$0.006 μsec). This feature permits a separation of photomultiplier signals into those due to plastic scintillation light and cesium iodide scintillation light. Charged cosmic ray particles which traverse the entire assembly can therefore be separated from gamma rays which produce detectable signals ordinarilly in only the cesium iodide. As flown, the instrument includes no provision for determining gamma ray arrival directions, and so the detected quantity was the INTEGRAL ~~isotropic~~ cosmic gamma ray intensity in the region 0.1 to 1 MeV.

The first measurement that provided convincing evidence for low energy gamma radiation from a discrete source was provided by the balloon-borne apparatus of Clark (3). Here again, a scintillation counter was used. It was very thin (1 mm thick) and was provided with a collimator of brass slats which limited the field of view to ±16° in one direction and ±55° in the other. No plastic scintillator or other special provision for eliminating incident charged particles was used. Rather, only energies in the regions 9-15, 15-28, 28-42, and 42-62 KeV were recorded. Incident charged particles would dissipate at least 1 MeV in the thin counter and so did not contribute directly to the detected signals. The apparatus was suspended so that the detector axis pointed 35° from the vertical and rotated slowly about a vertical axis. A large part of the visible sky was therefore scanned repeatedly. A detectable signal well above the background noise was found at the approximate location of the Crab Nebula. The physical mechanism responsible for the generation of these gamma rays and the more abundant x-rays at lower photon energies is not at all clear. The radio and much of the optical radiation from the Crab Nebula is certainly synchrotron radiation. There are some indications that x-rays and gamma rays too are synchrotron radiation but the energies of the implied electrons in this case are much too high to be accommodated in any of the current theories of the physical conditions within the nebula. Dr. Clark and his co-workers at MIT have improved the background rejection and enlarged the basic detector just discussed. With this improved instrument, shown in Fig. 3, flown by balloons from launch sites in both the United States and Australia, they have recently completed a survey of the entire sky. About a dozen sources have been found, most of which have positions which correspond at least approximately to the positions of known x-ray sources. Few (in fact only two or three) of the discrete x and gamma ray sources have been located in celestial coordinates well enough to permit unambiguous identification with objects that can be studied in visible light with ground-based telescopes.

Particularly the groups at the University of California at San Diego (UCSD) under Dr. L. Peterson and at NASA's Goddard Space Flight Center (GSFC) under Dr. K. Frost have been active in developing gamma ray detectors with excellent background rejection properties sensitive in the MeV region. In studies of discrete sources, one of course wishes to design a detector sensitive only over a narrow range of directions. Since gamma rays cannot be focussed as can light and radio waves, mechanical collimators must be used. In the x-ray region and gamma ray region in the tens of KeV, this collimation can be provided, for example, by thin sheets of brass. At larger energies, much thicker collimators are required to prevent detection in unintended directions. Unfortunately, charged cosmic ray particles and other gamma rays can and do interact in thick collimators and the secondary particles or gamma ray can then enter the sensitive volume of the detector and be counted as unwanted background. The UCSD and GSFC scheme involves the use of a mechanical collimator thick enough for its intended purpose, but made itself of scintillating material. The electronic circuitry is arranged in such a way that gamma rays detected by the inner scintillation counter are recorded only if no simultaneous radiation is detected in the surrounding massive cesium iodide counter. A line drawing of an instrument of this type developed by the USCD group is shown in Fig. 4. Here the sensitive directions include about 25.5°. A similar but much larger instrument with about 8° angular resolution is shown in Figure 5. It also was developed by the UCSD group. Fig. 6 shows an instrument of the same type, but prepared by the GSFC group for flight on one of the OSO series of spacecraft.

Much of the low energy cosmic ray data that we have, particularly information on source energy spectra, have been gathered with howitzer-type instruments carried aloft with balloons or flown in satellites. Figure 7 shows a typical balloon system for carrying and orienting a detector of this type. It was used by Dr. R. Haymes and his co-workers at Rice University in their study of the gamma ray energy spectra of the Crab Nebula and from the Cygnus region (5, 6).

Proportional counters have been widely used in cosmic x-ray investigations and have been used to some extent in gamma ray investigations too. As far as the physics of the conversion of gamma ray (or x-ray) energy into electrons is concerned, the operation is entirely similar to a scintillation counter. The one or more high speed electrons collide repeatedly with gas atoms creating a large number of ionized gas atoms and free electrons. The free electrons are attracted to a central wire or anode which is at a high positive potential. Near the wire, a cascading process takes place in which each incoming electron produces up to several thousand additional electrons. The collection of all these electrons then constitutes a pulse of charge which can be amplified and measured electronically. The magnitude of the charge pulse is proportional to the energy of the gamma ray. Here the energy resolution is limited by the finite number of ion pairs produced. Since in most gases the average energy required to create an ion pair is near 30 eV, a gamma ray of 0.03 MeV will produce only N = 1000 ion pairs. The energy resolution is therefore typically $1/\sqrt{N} = 3\%$ at 0.03 MeV and therefore superior to that of a scintillation counter. But the detection of gamma rays of energy much in excess of 0.06 MeV with proportional counters is impractical because of the difficulty in confining a suitably large mass of gas to a reasonable volume.

Boldt and Serlemitsos of GSFC have developed a gamma ray detector, shown in Fig. 9, which consists of many small proportional counters separated from each other only by very fine wires. Similar schemes have proven very effective in reducing background in x-ray detectors. Ideally, the pulses from each of the anodes is amplified and recorded separately so that x or gamma rays which deposit their energy in one or at most two or three counter segments can be recognized and distinguished clearly from incident charge particles which are more apt to deposit their energy in many segments.

Proportional counters have not yet had wide use in low energy gamma ray investigations. Figure 10 shows a balloon-borne apparatus developed and used by R. Sullivan and J. McClintock of MIT for investigations particularly of the radio galaxy M-87.

The last and probably most promising low energy gamma ray device is the solid state detector. As with the gas proportional counter and scintillation counter, gamma ray energy is determined correctly provided all of the gamma ray energy is transferred to electrons which in turn loose all of their energy in the sensitive mass of the detector. The important feature of the solid state detector is the very small amount of energy required to produce an electron-hole pair. For Lithium-drifted Germanium, this energy is about 2.9 eV so that a 0.03 MeV gamma ray produces about N = 10,000 electrons for a theoretical energy resolution of $1/\sqrt{N} = 1\%$. At small gamma ray energies the resolution is limited not by statistical consideration, but by the inherent detector and pre-amplifier noise. For small detectors and low noise pre-amplifiers cooled to liquid nitrogen temperatures, the state-of-the-art noise limitation corresponds to about 500 eV so that the statistical and inherent noise contributions to the energy resolution become equal at about 0.03 MeV. Energy resolution is of utmost importance in attempts to detect monoenergetic gamma rays from radioactive nuclear decay when there is a background of more or less continuously distributed gamma ray energies present.

Several groups have developed balloon-borne solid state detectors for low energy gamma ray investigations. The instrument developed by Drs. Overbeck and Womack of MIT and shown in Fig. 11 is very similar though appreciably larger than an instrument developed by Drs. Peterson and Jacobson of UCSD. Collimation in both cases is provided by active scintillation counter shields. In addition to the usual problems of telemetry, orientation, etc., there is the difficult complication of flying the cryogenic apparatus needed to keep the detector and its preamplifier cooled to liquid nitrogen temperature. Figure 12 is a photograph of the UCSD apparatus mounted in its orientation mechanism.

A group at Oak Ridge National Laboratory under Dr. J. H. Gibbons is developing a very large cooled solid state instrument for low energy gamma ray investigations aboard one of NASA's Apollo Applications Programs missions. A preliminary version is shown in Fig. 13. The long collimator provides an angular resolution of about 3°. While the MIT and UCSD devices as well as the Oak Ridge device have flown successfully on balloon-borne instruments, it seems likely now that long exposure with large instruments will be necessary to detect nuclear gamma ray line radiation.

The broad gamma ray energy region between several MeV and about 100 MeV remains virtually unexplored. There are certainly interesting and important questions to be answered by observations carried out in these energies, but the detection problems are formidable. Absorption probabilities are small, which means that the mass of apparatus for total absorption of the gamma ray energy is very large. Further, collimation is very difficult. Gamma ray absorption by Compton scattering and by photo-electric absorption are negligible and only pair production is important. That this is so, however, can be used advantageously at higher gamma ray energies. This is because the electron-positron pair emerge from a pair production process at an angle which is near (mc^2/E) radians to the direction of the gamma ray. Of course the pair production process must necessarily take place in matter of some sort, and in getting out of this matter (the pair converter) the electrons scatter in their encounters with atomic nuclei. In most practical situations, it is the multiple scattering of the electrons that determines the accuracy with which the gamma ray arrival direction can be inferred from the electron (and positron) directions.

One of the first high energy gamma ray investigations used a combination of a heavy lead shield and pair direction to define the gamma ray arrival direction. The detector was designed by Dr. T. Cline, then of MIT, now at GSFC and is shown in Fig. 14. Gamma rays passed through the two plastic anti-coincidence or veto counter plastic scintillation counter shields and were converted into electron-positron pairs in the mercury converter. (The mercury absorber was removed during actual operation and was only in the position shown for background evaluation studies.) The pairs were next detected in a thin cesium iodide scintillation detector and then in the Lucite Cerenkov counter. (When a charged particle traverses a transparent substance it emits light in a cone of half angle θ such that $\cos\theta = c/vn$ where c is the velocity of light, v is the velocity of the particle and n is the index of refraction of the transparent substance. If v is less than c/n, no Cerenkov light is emitted). The detection of a light pulse from the Cerenkov counter guaranteed that the charged particles were travelling down, not up through the apparatus and similarly guaranteed that they were fast light particles (electrons) not slow protons. The lack of detectable pulses from the two plastic veto counters insured that the incident particles were electrically neutral. Cline's experiment was successful in establishing meaningful upper limits to the gamma ray flux from a variety of likely sources, but did not detect a definite extraterrestial flux (7).

The first satellite high energy gamma ray investigation was flown as Explorer XI, and was developed at MIT by Dr. Clark and the author of this article. It is shown schematically in Fig. 15. The principle of detection is similar to the scheme of Cline, except that only the electron-positron pair direction is used to define the gamma ray direction. Again the results could be strictly interpreted as only providing upper limits to the cosmic high energy flux. There was, however, a marginally significant indication of an enhanced flux from the galactic plane or Milky Way (8).

A much improved version of the Explorer XI instrument was designed by Clark, Garmire, and the present author for flight on the third Orbiting Solar Observatory (OSO III). It is shown in Fig. 16. Gamma rays are converted into electron-positron pairs in one of the top layers of scintillation counter. The pair is detected there and also in the Cerenkov counter and in the layered energy-calorimeter at the base of the instrument. The calorimeter consists of alternate layers of sodium iodide and Tungsten so as to provide the large mass of material required to make an energy measurement of high energy electron-positron pairs. This instrument went into orbit early in March of 1967 and is still operating. A definite flux of high energy gamma rays coming preferentially from the galactic plane has been detected (9). The intensity is large — too large to be accounted for by a simple application of the production mechanism ideas outlined earlier in the article — but in approximate agreement with the tentative results mentioned above from the Explorer XI instrument. At this time, before our detailed analysis is complete, we can only conclude that there are likely more cosmic ray type particles confined to the galactic plane than we thought before.

While these two satellite experiments were being developed and flown, similar experiments were carried out by other groups, notably a group at Rochester under Drs. Kaplon, Duthie and Hafner, and a group at the University of New Mexico under Dr. C. Leavitt. At various times apparent positive results were obtained, but none survived attempted confirmation by later experiments. Simultaneously, the spark chamber technique, so useful in laboratory high energy physics investigations, was adapted to high energy cosmic gamma ray investigations.

A spark chamber consists of a number of parallel electrodes, spaced by up to 1/4" and filled with a Helium-Neon gas mixture. When external counters indicate that a particle has traversed the chamber, alternate electrodes are pulsed to about 10,000 volts. At the sites of ionization between the electrodes, the gas breaks down, forming a spark which can be photographed or otherwise recorded. The spark chamber, when used for high energy cosmic gamma ray investigations, has a very important advantage – an advantage which insures that it or some similar instrument will be the ultimate tool for good quality measurements. When a "telescope" of the OSO III or Explorer XI variety views the sky and records a gamma ray, one only knows that the gamma ray arrived from some direction within the rather large acceptance cone of the instrument. (For the Explorer XI and OSO III instruments this cone was about 25° wide.) With a spark chamber, on the other hand, a large solid angle can be viewed during one observation, but the spark tracks can individually be analyzed and associated with a gamma ray arrival direction to within about 1°.

A typical gamma ray spark chamber, developed for balloon observations by the Case-Western Reserve group under Dr. G. Frye, is shown in Fig. 17. The gamma ray conversion into electron-positron pairs occurs in one of the 30 thin stainless steel plates. The electron tracks can therefore be observed before the electrons have traversed much material in which scattering can take place. Triggering of the apparatus was provided by the two plastic scintillation counters and by the Cerenkov counter at the bottom. Cameras photograph the spark chamber in two stereoscopic views each time the chamber is pulsed.

A photograph of an entirely similar apparatus developed for balloon flight used by a group at the Smithsonian Astrophysical Observatory (Drs. G. Fazio and H. Helmken) is shown in Fig. 18. Here the spark chamber is not photographed, but viewed by a vidicon camera. The televised information is telemetered to the ground where it is recorded on film and magnetic tape.

A group at Cornell University under Dr. K. Greisen and a group at the University of Southampton (England) under Dr. G. Hutchinson have used microphones, two or three located at each electrode gap, to locate spark coordinates. The sparks are acoustically well defined, so that relative arrival times of the acoustic pulses at the microphone can be used for this purpose. The Cornell chamber was used for balloon-borne observations. The Southampton chamber was developed for flight on the NASA satellite, OGO-5, and is presently in orbit. It is shown in Fig. 19. Results are not as yet available.

Dr. C. Fichtel and his co-workers at the Goddard Space Flight Center have developed a wire electrode spark chamber for high energy cosmic gamma ray investigation. Alternate electrodes consist of planes of wires and the wires in one plane are spaced by 0.05". Between the wire electrodes are thin metal plates electrodes which serve also as gamma ray pair converters. Each wire passes through a small magnetic core so that information as to which wire sparked is available. Alternate electrodes are arranged with wires perpendicular and so provide both x and y coordinates. Two sets of wires are skewed 45° to the rest to eliminate ambiguities which arise when two or more particles are detected. Core readout for telemetry is accomplished by standard methods. The magnetic core readout-wire spark chamber has been used by the Fichtel group for several balloon flight experiments and a space-worthy model of the device shown in Fig. 20 is presently being prepared for flight on the second Small Astronomy Satellite(SAS-B).

While the spark chambers as described above are able to determine electron directions with small scattering error, the plates do have some finite thickness and particularly at small gamma ray energies (less than 100 Mev) the scattering errors are appreciable. Two groups, one at the University of Minnesota under Dr. J. Waddington and the other at Washington University under Dr. J. Klarmann have successfully used nuclear emulsions together with spark chambers to measure gamma ray arrival directions. The nuclear emulsions are mounted either over or actually within the spark chamber, and the spark chamber tracks are used only for locating the site within the emulsion that the gamma ray pair production process took place. In the emulsion the direction of the electrons can be determined close to their point of origin, before scattering effects have become serious.

Balloon-borne spark chamber instruments have good sensitivity for the detection of possible discrete high energy gamma ray sources, but are poorly suited to a diffuse or apparent line source such as has been detected in the OSO-III measurement. This is because with any balloon-borne experiment, there is bound to be 0.3% or more of the total atmosphere still above the apparatus. The absorption of incident gamma rays by this amount of matter is of no consequence. But there is created in this much air a relatively large gamma ray background by the nuclear interactions of charged cosmic ray particles. This background comes from all directions with approximately equal intensity, but the background flux from any given small area of sky, say one square degree, is small. A point source emitting a given flux, therefore, appears more clearly above the background noise than does a diffuse source, even if emitting the same total flux but spread over a large area of sky. The OSO-III instrument was able to detect a diffuse flux only because the background level was very small. None of the balloon-borne spark chamber devices flown to date have provided convincing independent evidence for any extra-terrestial gamma ray flux, discrete or diffuse. Recent observations by the Case-Western Reserve and University of Minnesota groups, however, do seem to provide supporting evidence for a flux from the galactic plane in the Cygnus region at about the level reported by the OSO-III experimenters.

Satellite-borne spark chamber instruments will not, of course, have to contend with atmospherically produced background and should be vastly superior to poor-angular-resolution instruments such as OSO-III. The GSFC digitized spark chamber scheduled to be flown on SAS-B in 1971 is a very important next step, both because of the new information on gamma rays that it should provide, and also because it will provide experience and essential engineering information needed for the optimum design of much larger instruments. It is clear that instruments appreciably larger than that to be flown on SAS-B will be needed because of the very small gamma ray flux levels to be expected from some of the most interesting objects.

An alternative scheme for good angular resolution detection of high energy cosmic gamma rays is currently being developed by Dr. G. Fazio of Smithsonian Astrophysical Observatory, Dr. K. Greisen of Cornell University, and Dr. M. Shapiro of the Naval Research Laboratories. The proposed device is shown in Fig. 21. Gamma rays enter from the left, pass undetected through a plastic veto or anti-coincidence counter (S-1) and enter the lead converter where electron-positron pairs are produced. The pairs pass through and are detected in a thin scintillation counter and then enter the large volume of low pressure gas where, if their velocity is great enough, the electrons emit Cerenkov light. Cerenkov light is focused by the mirror on to the array of seven photomultiplier tubes. The important features of the proposed instrument are its relative simplicity, large area, and expected excellent background rejection properties. The low pressure Cerenkov gas means that only very high velocity particles can be detected, thus eliminating a large portion of the potential (proton) cosmic ray background. Further, the photomultipliers which detect the Cerenkov light should get this precisely 3.2×10^{-8} seconds after the scintillation counter near the converter records the passage of the electron-positron pair. The instrument is currently being developed for balloon-flight testing and operation, with the expectation that it will eventually be flown on one of NASA's larger orbital scientific missions. For gamma rays above about 250 MeV, the angular resolution of the device is about 1°. The instrument does, of course, have to be pointed towards a suspected gamma ray source for extended periods of time and is probably not well suited to an all-sky survey.

Early in the article, I mentioned a very ingenious method that has been developed to investigate from the ground the possible flux of very energetic cosmic gamma rays. When a very high energy gamma ray enters the Earth's atmosphere, it penetrates a short distance, but eventually makes an electron-positron pair. The pair, having also high energy, penetrate further and eventually collide with atomic nuclei to produce more gamma rays. These gamma rays penetrate more, and produce more pairs. In this way a shower of energetic particles builds up and the shower may contain hundreds of even many thousands of particles at the height of its maximum development. The electrons and positrons, being charged particles, emit light by the Cerenkov process and at least while they still have high energy, the direction of their emitted light will correspond very closely (to within a degree or so) to the direction the incoming gamma ray had when it entered the atmosphere. Quantitative arguments show that this light should be detectable from the ground, provided the energy of the incoming gamma ray is 1000 BeV or so. The exact threshold depends upon the size of the light collectors or telescope. Light from showers is easily distinguished from star light because the Cerenkov light from showers arrives all at once in a sudden burst while starlight is steady with only random statistical fluctuations. Showers which originate from charged cosmic ray particles produce a large and significantly limiting background. Cerenkov light from gamma ray induced showers cannot be directly distinguished from that due to particle induced showers. But charged cosmic ray particles arrive at the earth isotropically, whatever their source. This is because random magnetic fields in interstellar space thoroughly twist and confuse charged particle trajectories. Gamma rays, on the other hand, come directly, source-to-observer, as does light. In practice, then, a telescope being used for gamma ray detection via Cerenkov air shower light is made to scan across the position of a suspected source and the rate of detected light pulses is recorded and examined for possible increases correlated with celestial position. Several groups have been responsible for the development and use of this technique. They are led by Dr. A. Chudakov of the Lebedev Institute in Moscow, Dr. J. Jelley of the Atomic Energy Research Establishment in England, Dr. Neil Porter of University College, Dublin, and Dr. G. Fazio of the Smithsonian Astrophysical Observatory. In Fig. 22 is shown a recently completed optical reflector constructed by the Smithsonian Astrophysical Observatory specifically for gamma ray air shower studies. It is located on Mt. Hopkins in Arizona. To date none of the air shower investigations have detected a high energy gamma ray flux that has been unambiguously confirmed. The Mt. Hopkins reflector is just now starting a regular observing program, however, and results are eagerly awaited. Because of its great size and ideal location (good quality observations can only be made on clear, moonless nights) the Mt. Hopkins equipment will have many times the sensitivity of the similar but smaller equipment used previously.

This, then, is a brief report of the status of gamma ray astronomy. It is a young field with, if past experience with radio and x-ray astronomy is a fair index, a promising future. I have emphasized the instrumental aspects of the problems that exist, because it seems to me that it is here that the field is in serious need of new developments and ideas. Radio and x-ray astronomy emerged as astronomical tools with a rich laboratory and even industrial heritage. Gamma ray detection seems hard. Maybe it really is. But maybe we just need ideas from a broader interested group of people.

Figure Captions

Fig. 1 Height in the earth's atmosphere to which detecting apparatus must be carried in order to detect directly more than 50% of the incident cosmic electromagnetic radiation. For the purposes of this article, gamma rays are taken to mean radiation with wavelength smaller than 0.5 Angstrom units, or photon energy greater than about 25 KeV.

Fig. 2 Low energy gamma ray detector flown on Ranger. (1, 2)

Fig. 3 Balloon-borne low energy gamma ray detector of Clark, Lewin and Smith. (4)

Fig. 4 Howitzer type of low energy gamma ray detector developed by the UCSD group under Dr. L. Peterson. The collimation of the gamma ray is provided by the active scintillation material which surrounds the inner gamma ray detector.

Fig. 5 Advanced version of a detector of the type described in Figure 5.

Fig. 6 Howitzer type of gamma ray detector fabricated and ready for satellite flights on one of the OSO (Orbiting Solar Observatory) spacecraft. (GSFC)

Fig. 7 Balloon orientation system used by Haymes and Craddock in their investigation of gamma rays from the Crab Nebula.

Fig. 8 One of the Orbiting Solar Observatory (OSO) spacecraft. As the name implies, the primary purpose of this spacecraft is for solar investigations. The solar cell panel and perpendicular cluster of small aperture instruments points steadily at the sun when the satellite is on the sun-lit side of the earth. The wheel section beneath rotates at about 0.5 revolutions per second and so instruments mounted in the wheel which ordinarily view out along a radius scan a plane in the sky once every two seconds. This spacecraft has carried several gamma ray instruments into orbit.

Fig. 9 Proportional counter x and gamma ray detector developed by Drs. Boldt and Serlemitsos of GSFC.

Fig. 10 Balloon apparatus orientation system developed by MIT group for cosmic gamma ray measurements.

Fig. 11 Solid-state gamma ray detector in its sodium iodide howitzer collimator (MIT).

Fig. 12 UCSD solid-state gamma ray detector mounted with its cryogenic system in the balloon apparatus.

Fig. 13 Proposed solid-state gamma ray detector being developed for NASA's Apollo Applications Program by Oak Ridge National Laboratory.

Fig. 14 Balloon-borne high energy gamma ray detector developed by T. Cline.

Fig. 15 Gamma ray detector flown in 1961 as Explorer XI.

Fig. 16 Improved gamma ray detector flown in 1967 aboard OSO-III.

Fig. 17 Cosmic gamma ray spark chamber developed for balloon flights by the Case-Western Reserve group.

Fig. 18 Spark chamber apparatus developed for balloon-borne gamma ray measurement by the Smithsonian Astrophysical Observatory. The spark chamber is not photographed, but is viewed stereoscopically by a vidicon camera.

Fig. 19 Acoustic spark chamber developed by the Southampton group for flight on OGO-5.

Fig. 20 Magnetic core read-out high energy cosmic gamma ray spark chamber being prepared by GSFC for flight in 1971 on the Small Astronomy Satellite (SAS-B).

Fig. 21 High energy gamma ray detector being developed jointly by Cornell University, Smithsonian Astrophysical Observatory, and the Naval Research Laboratory.

Fig. 22 Optical reflector for the detection of Cerenkov light generated by gamma ray induced air showers. The 10 meter reflector, developed by the Smithsonian Astrophysical Observatory, is located on Mt. Hopkins, Arizona.

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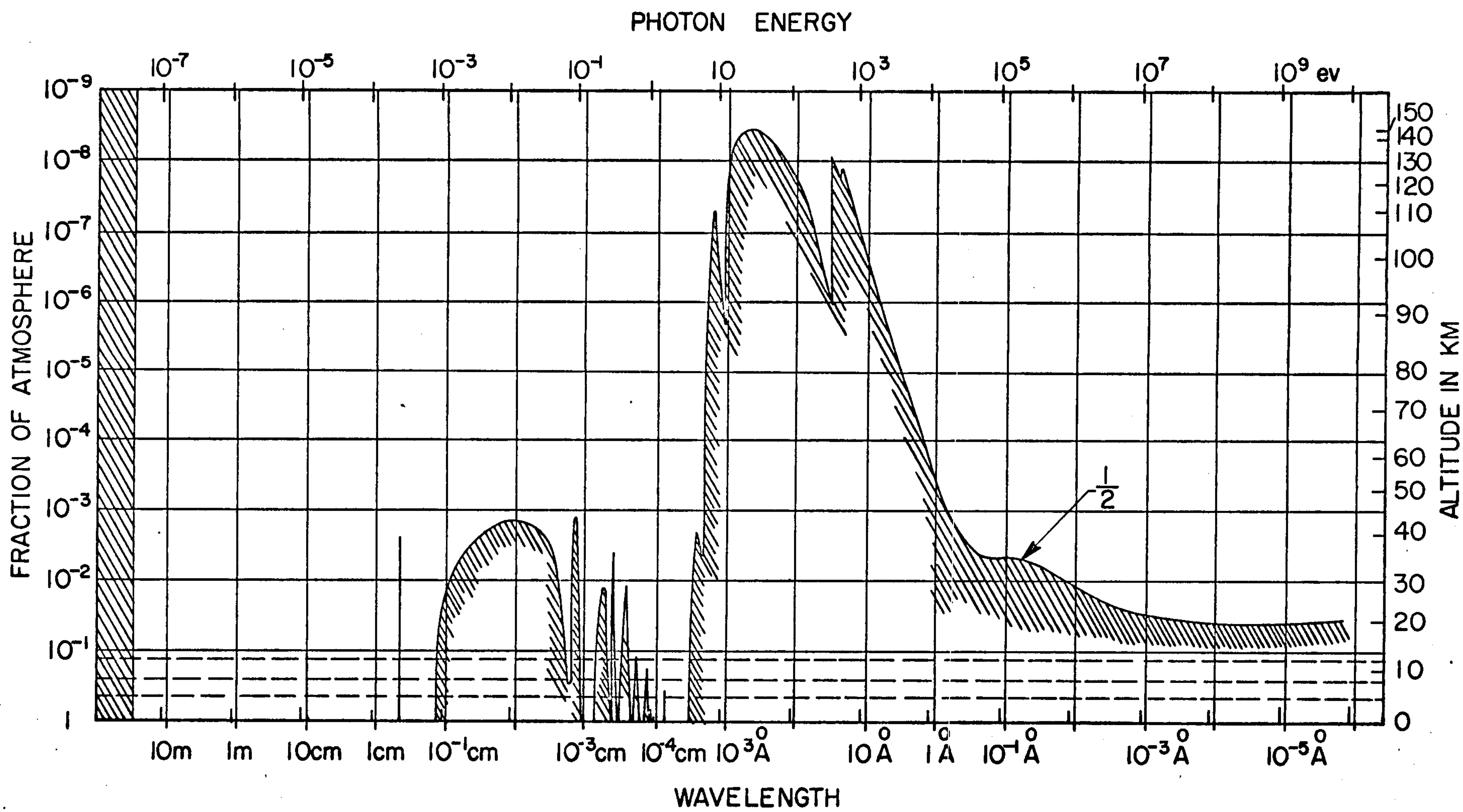
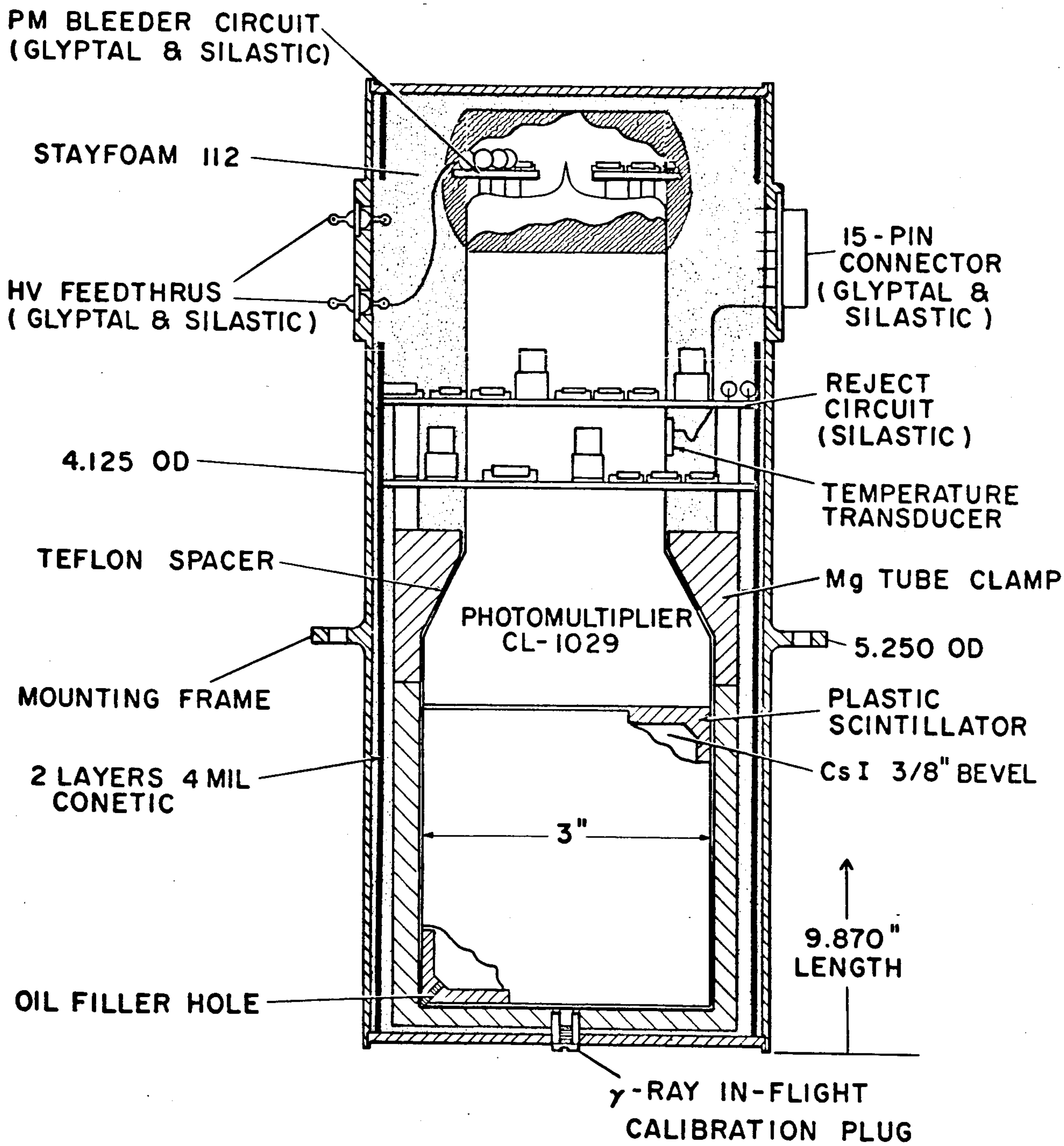
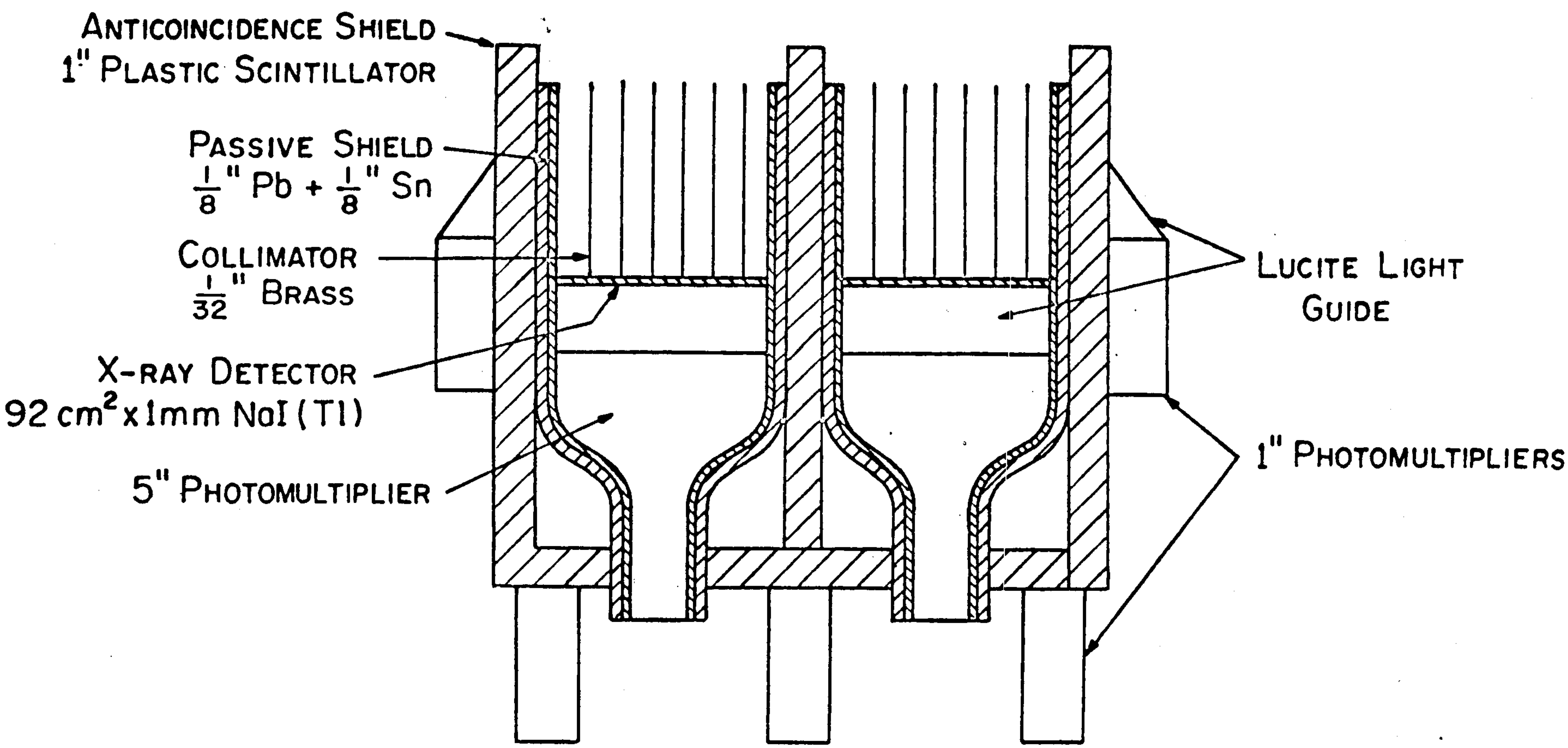


PHOTON ENERGY
10-7
10-5
10-3
10-1
10
10^3
10^5
10^7
10^9 ev
FRACTION OF ATMOSPHERE
10-9
10-8
10-7
10-6
10-5
10-4
10-3
10-2
10-1
1
ALTITUDE IN KM
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
1/2
10m
1m
10cm
1cm
10-1cm
10-3cm
10-4cm
10^3Å
10Å
1Å
10-1Å
10-3Å
10-5Å
WAVELENGTH

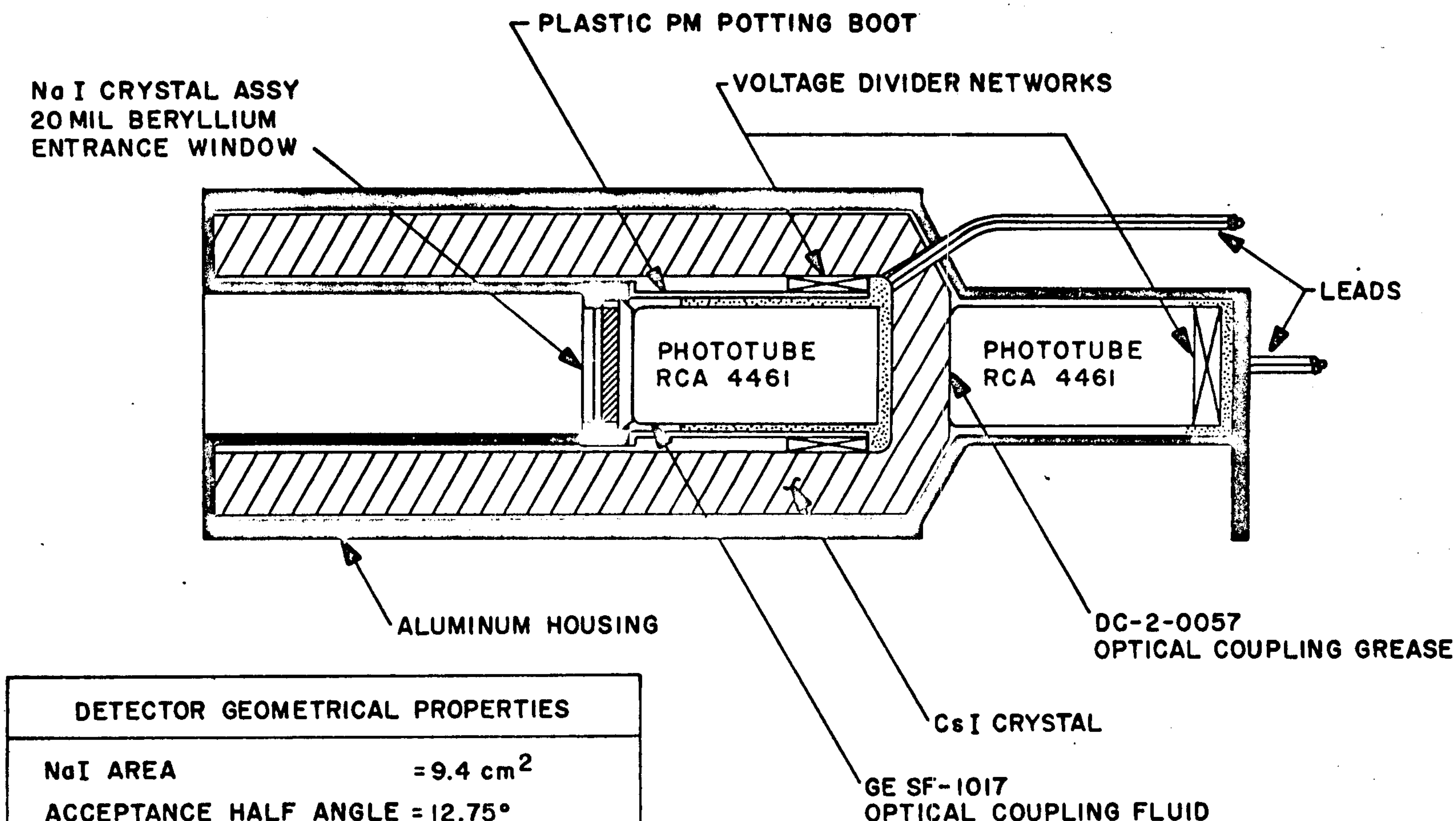
Fig 1



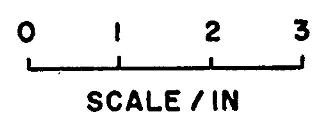
RANGER GAMMA-RAY DETECTOR

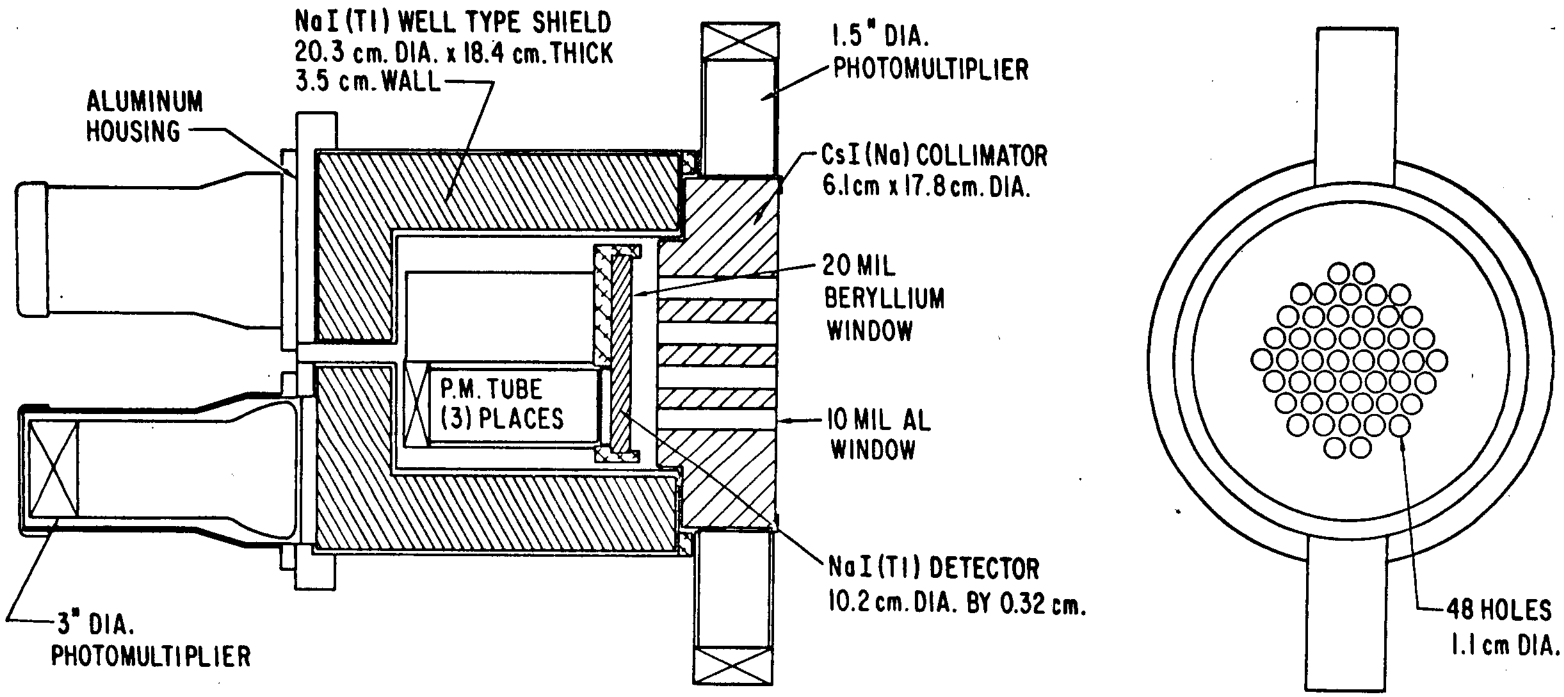


Anticoincidence Shield
1" Plastic Scintillator
Passive Shield
1/8" Pb + 1/8" Sn
Collimator
1/32" Brass
X-ray Detector
92 cm² x 1mm NaI (Tl)
5" Photomultiplier
Lucite Light
Guide
1" Photomultipliers



DETECTOR GEOMETRICAL PROPERTIES	
NaI AREA	= 9.4 cm^2
ACCEPTANCE HALF ANGLE	= 12.75°
NaI TELESCOPE FACTOR	= 1.5 STERAD-cm^2
CsI GEOMETRY FACTOR	= 210 cm^2

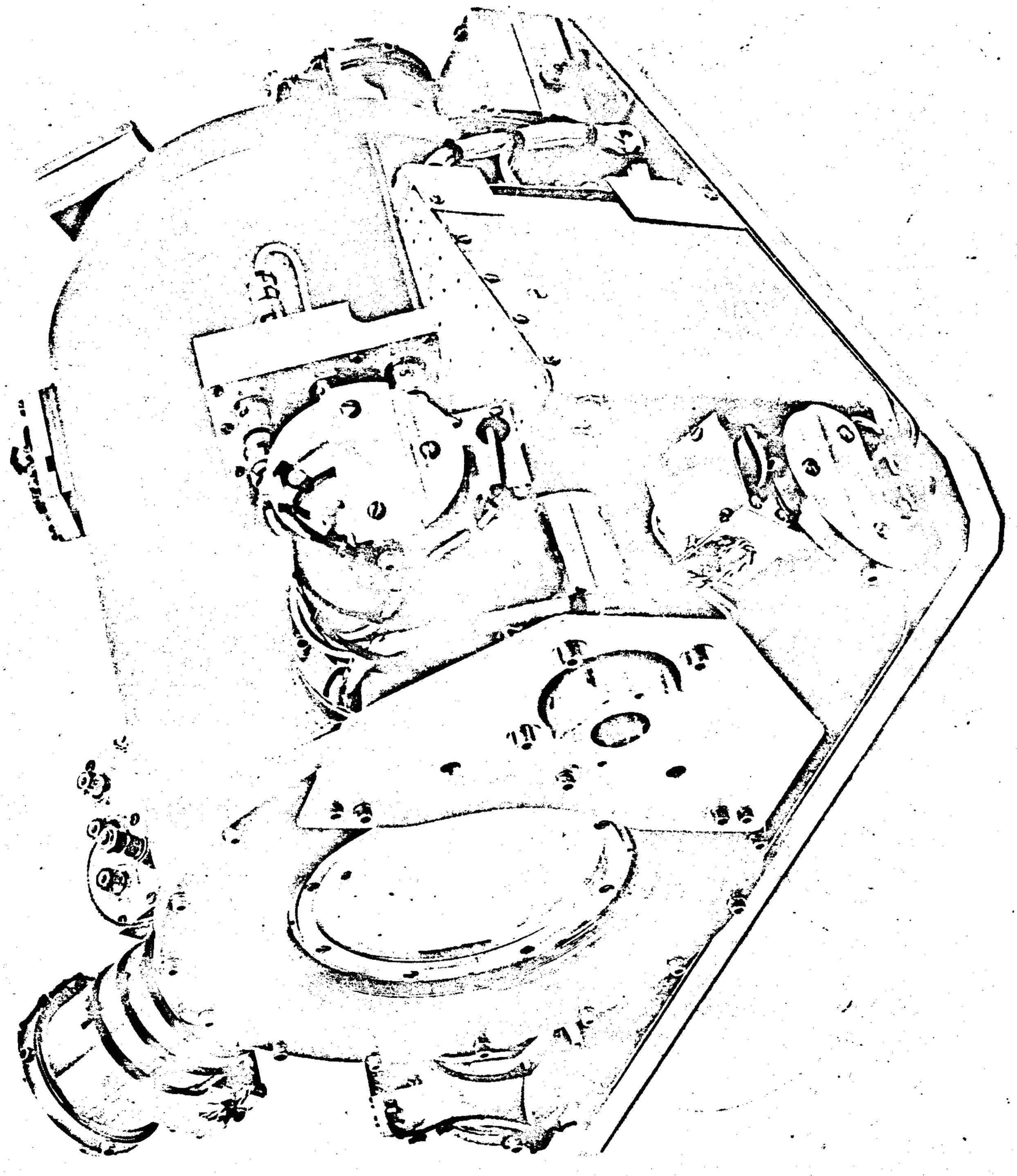


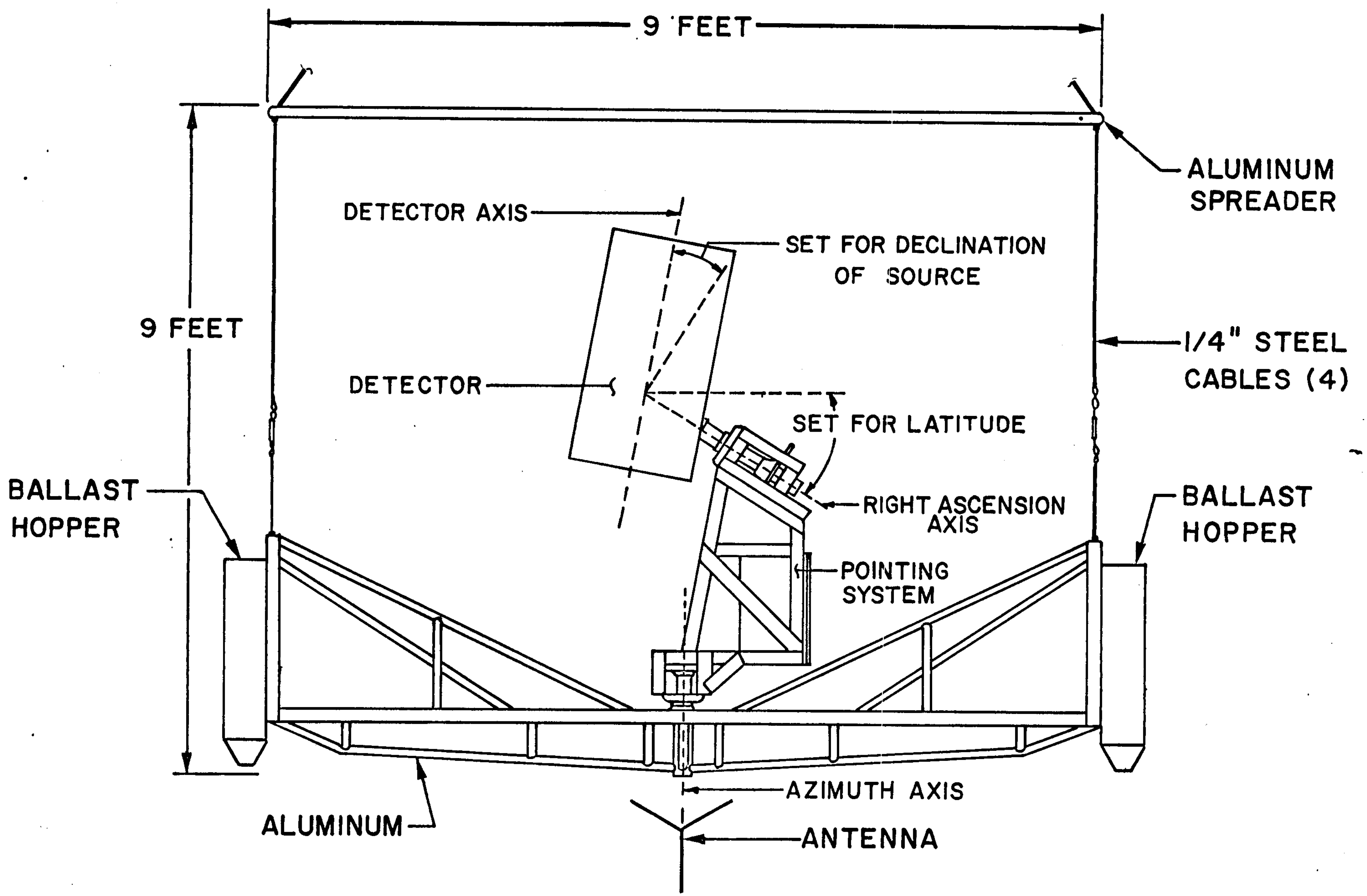


DETECTOR GEOMETRICAL PROPERTIES	
DETECTOR AREA	= 46.3 cm^2
ACCEPTANCE HALF ANGLE	= 4.2°
	= 2.5×10^{-2} STERAD
TELESCOPE FACTOR	= 1.16 STERAD - cm^2
GEOMETRY FACTOR (SHIELD)	= 455 cm^2

HONEYCOMB COLLIMATED X-RAY DETECTOR

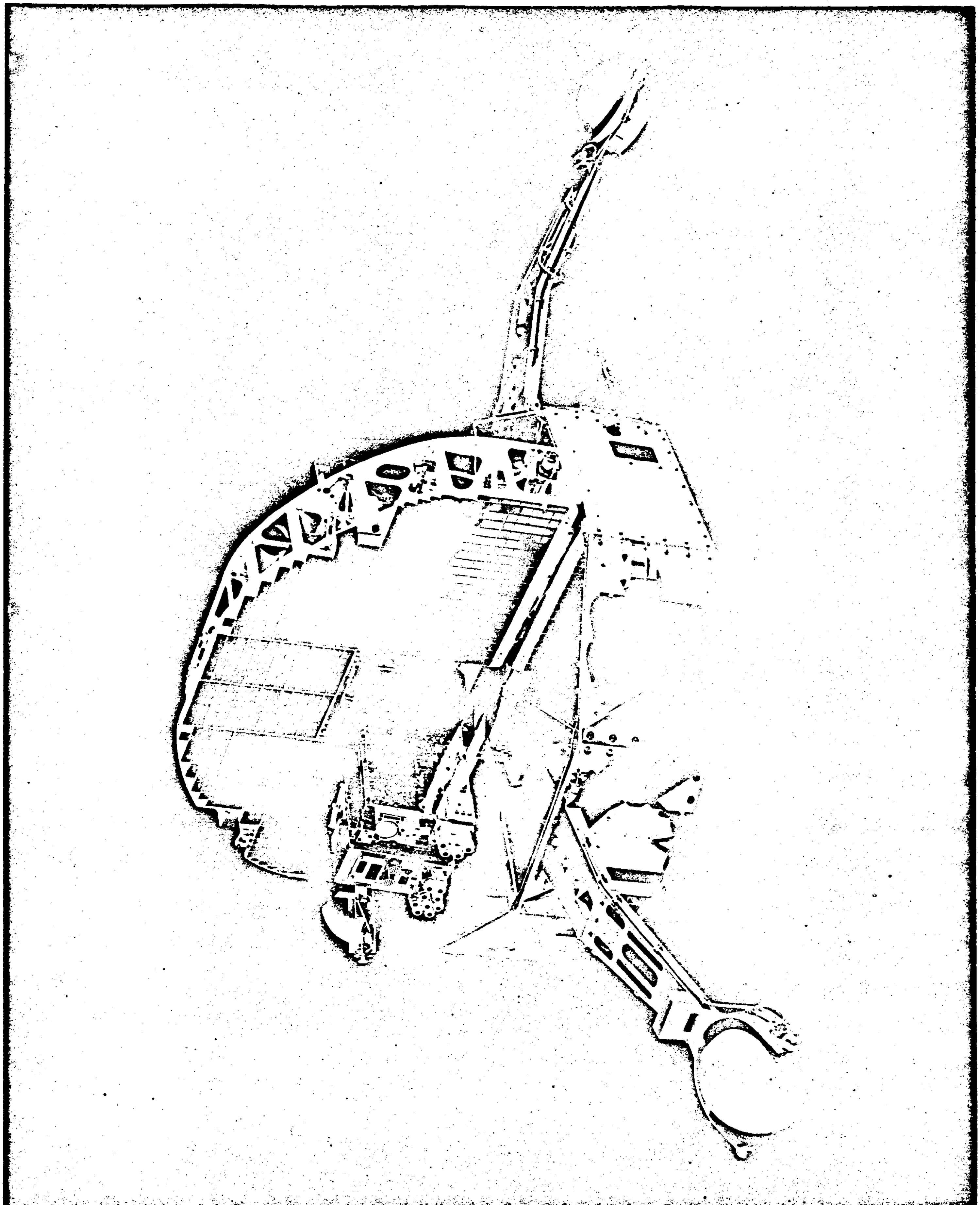
10-300 KeV

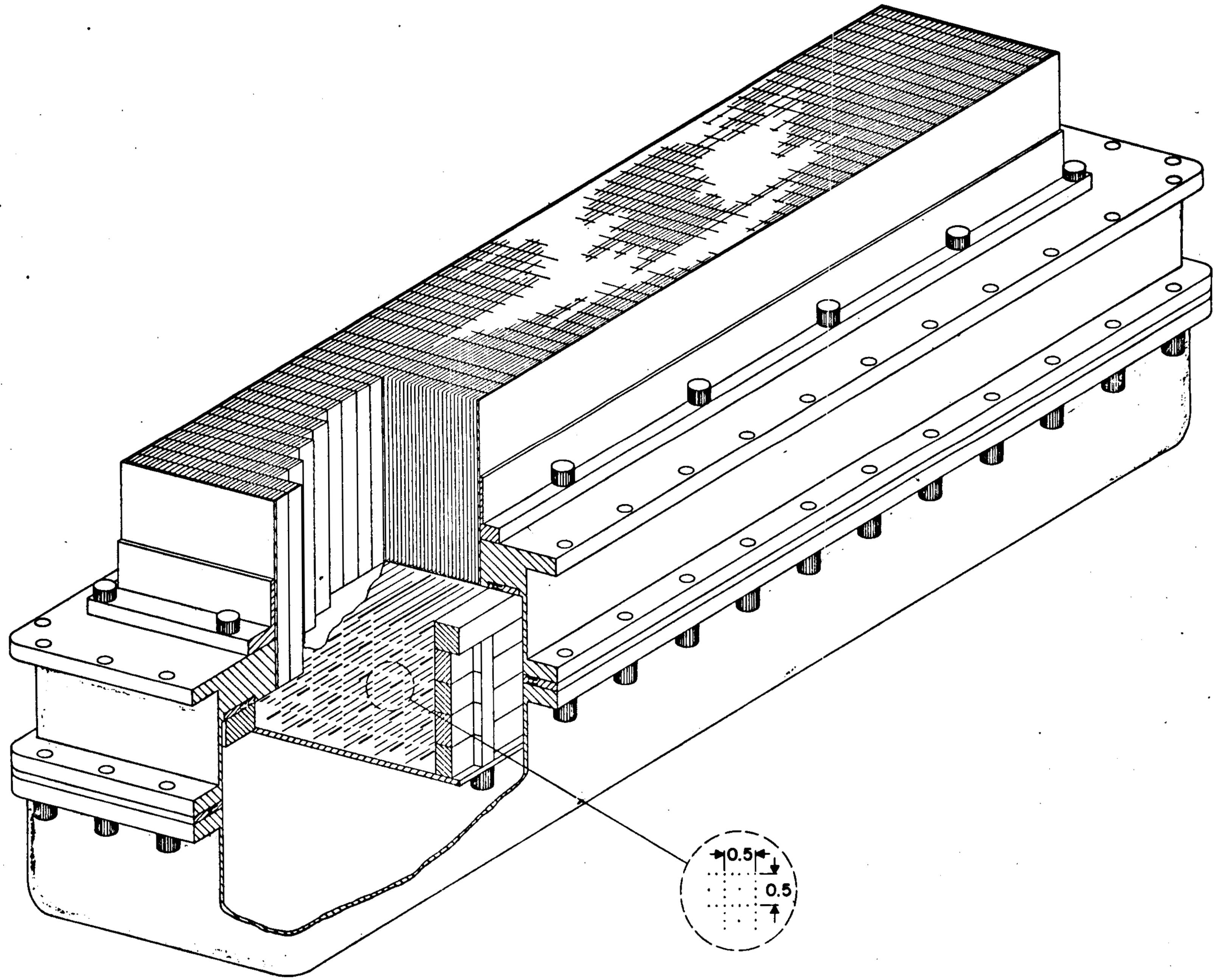




BALLOON BORNE SYSTEM

201508





X-RAY PROPORTIONAL CHAMBER (Δ-PAC)

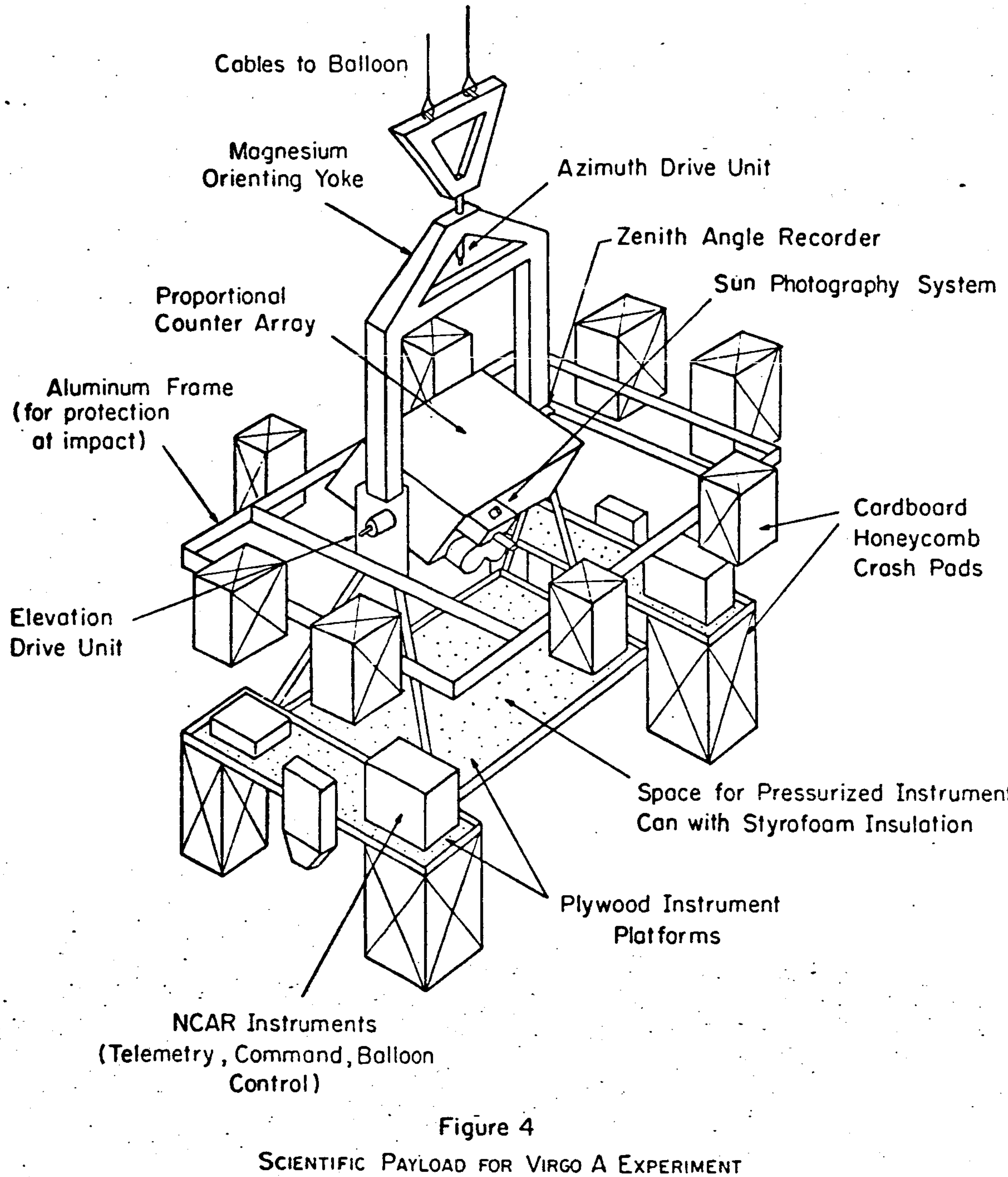
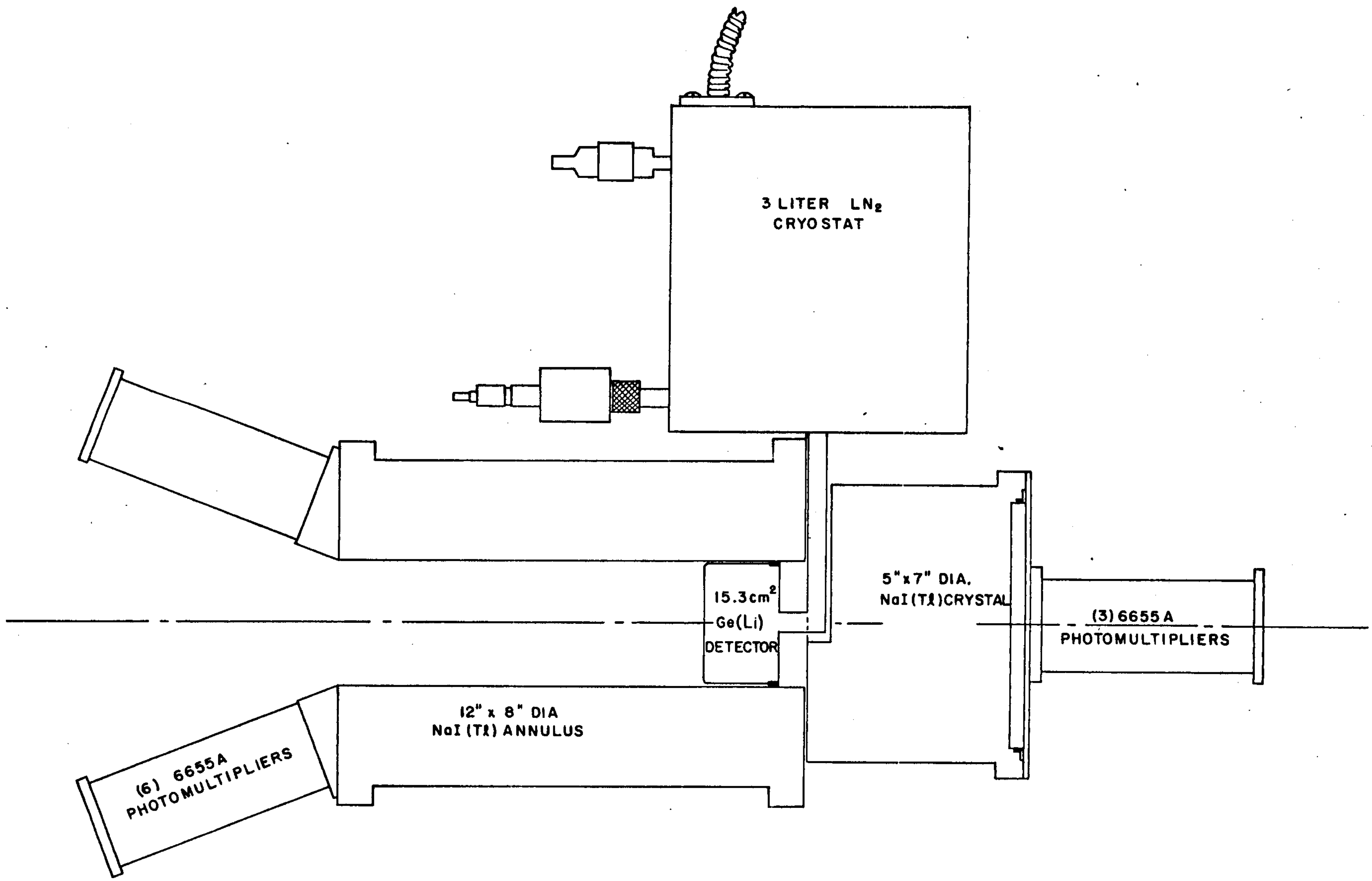


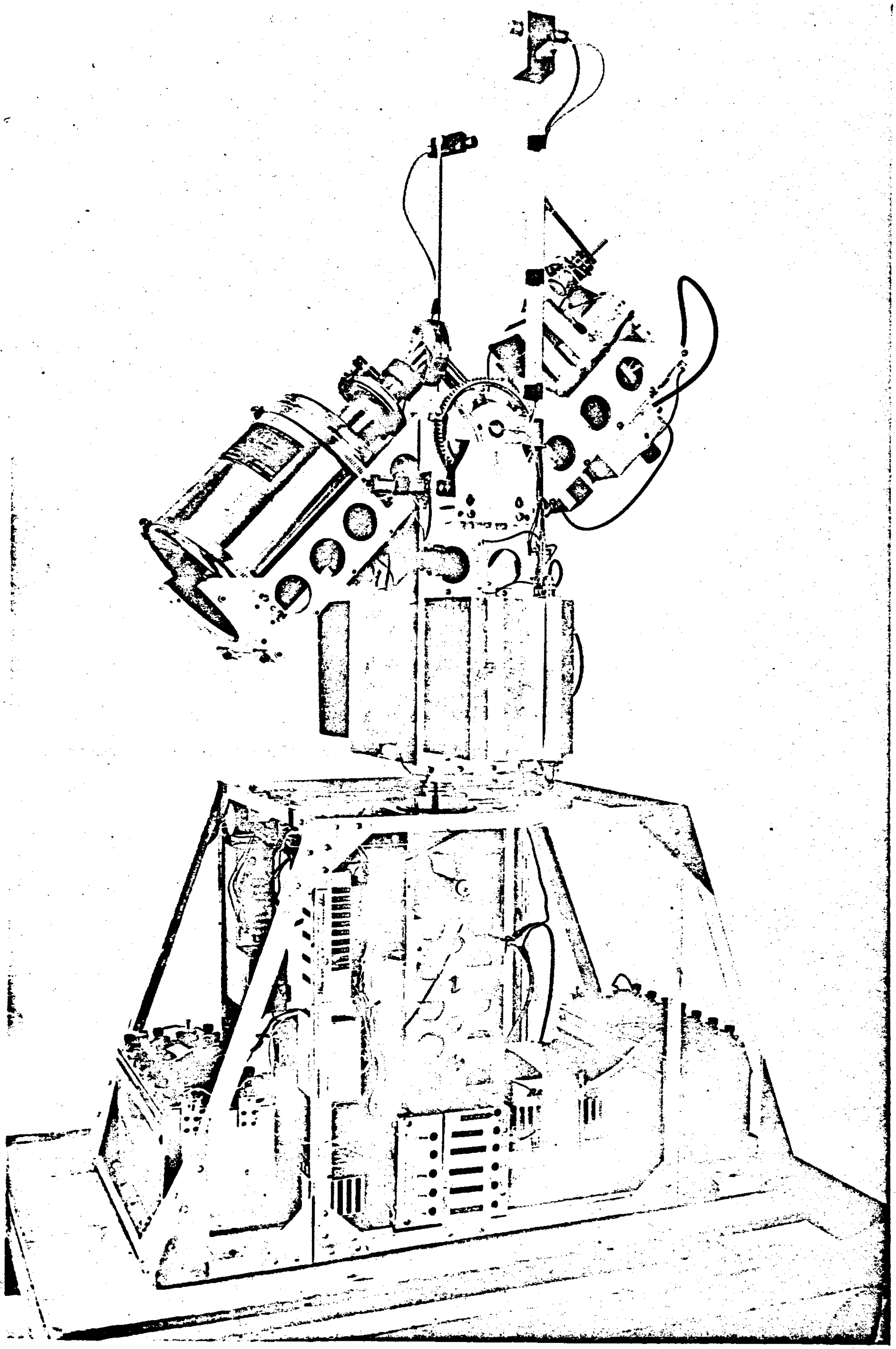
Figure 4

SCIENTIFIC PAYLOAD FOR VIRGO A EXPERIMENT

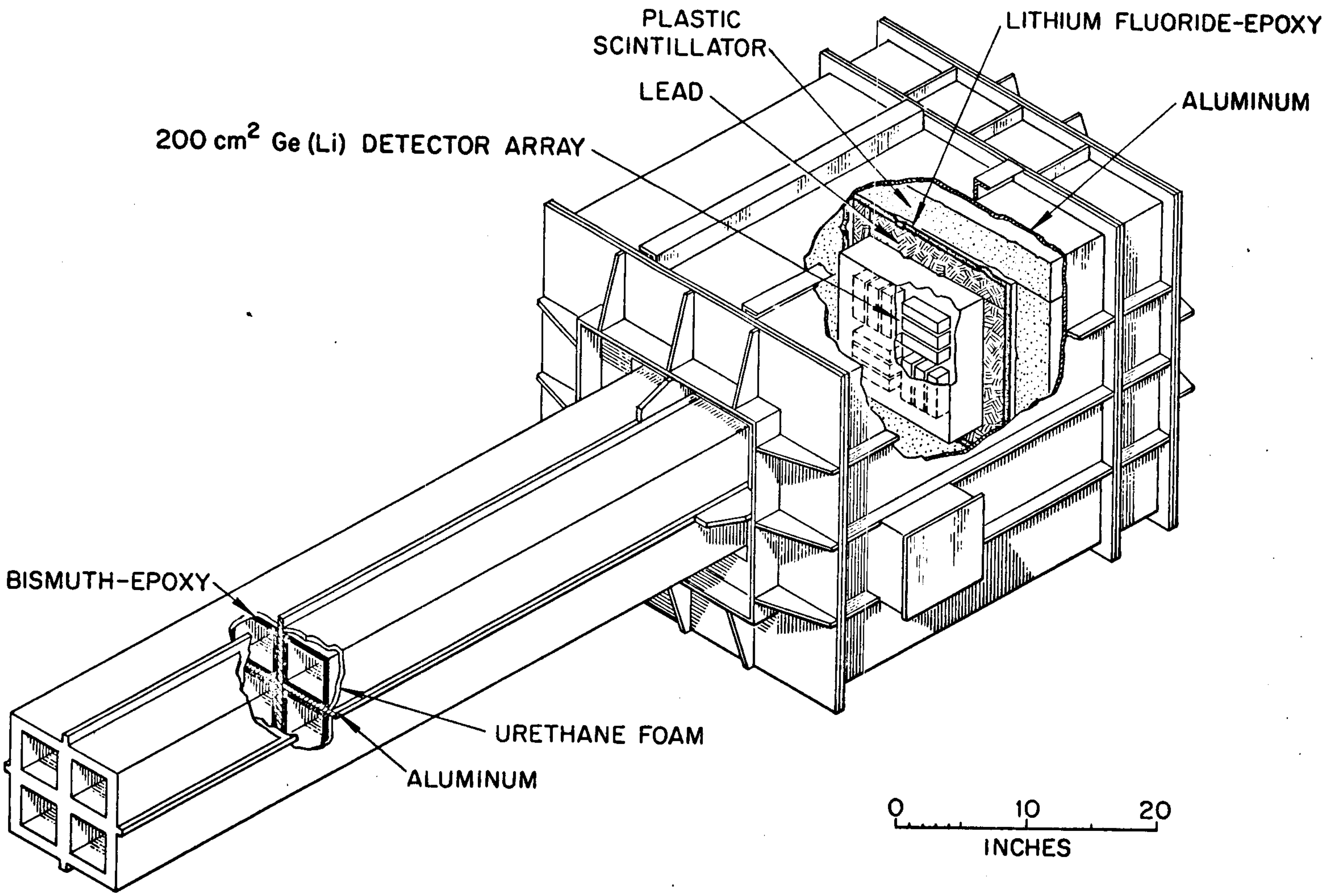
(Not to scale, Actual Total Height = 16')

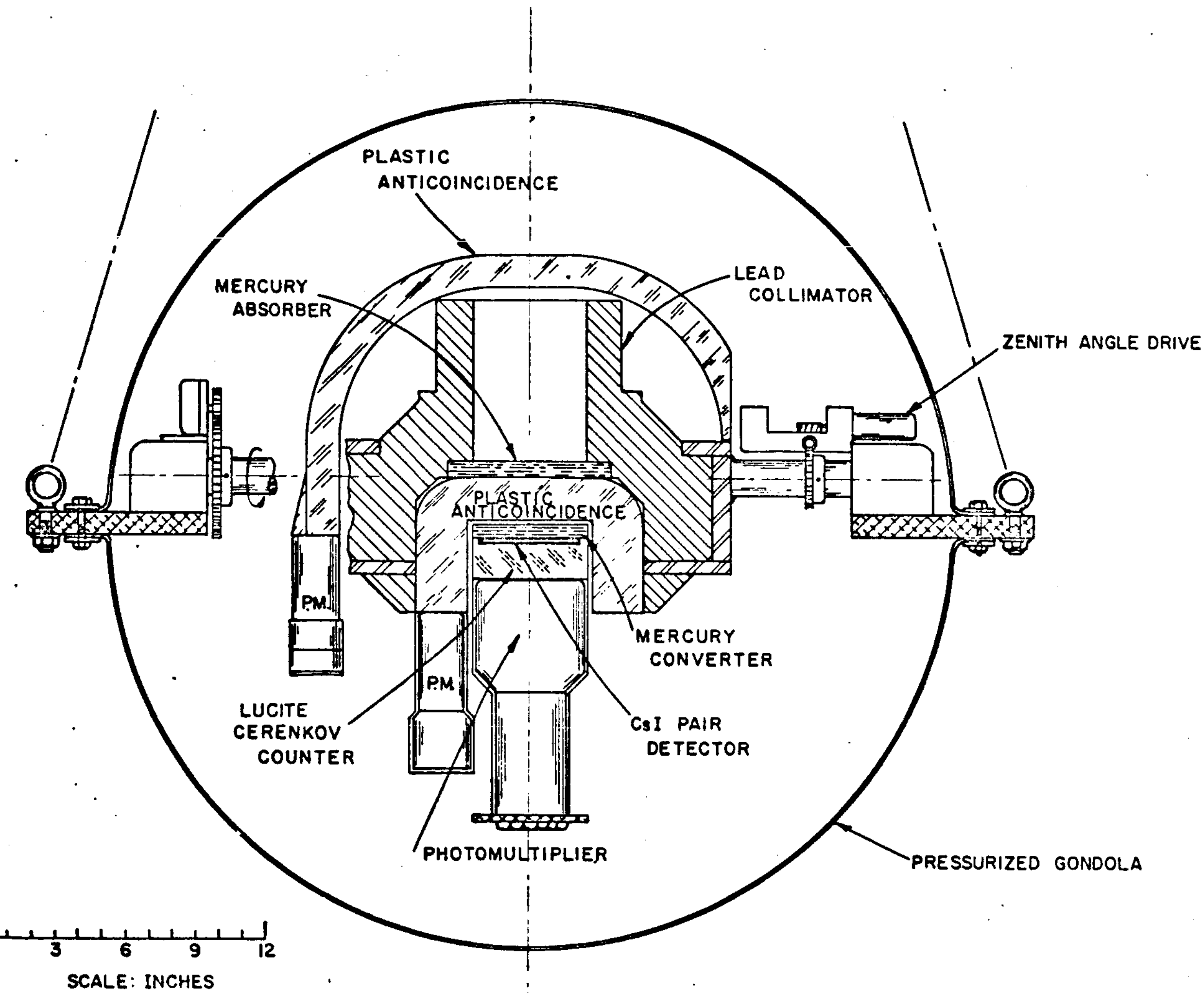


SEMICONDUCTOR SPECTROMETER FOR
GAMMA RAY ASTRONOMY

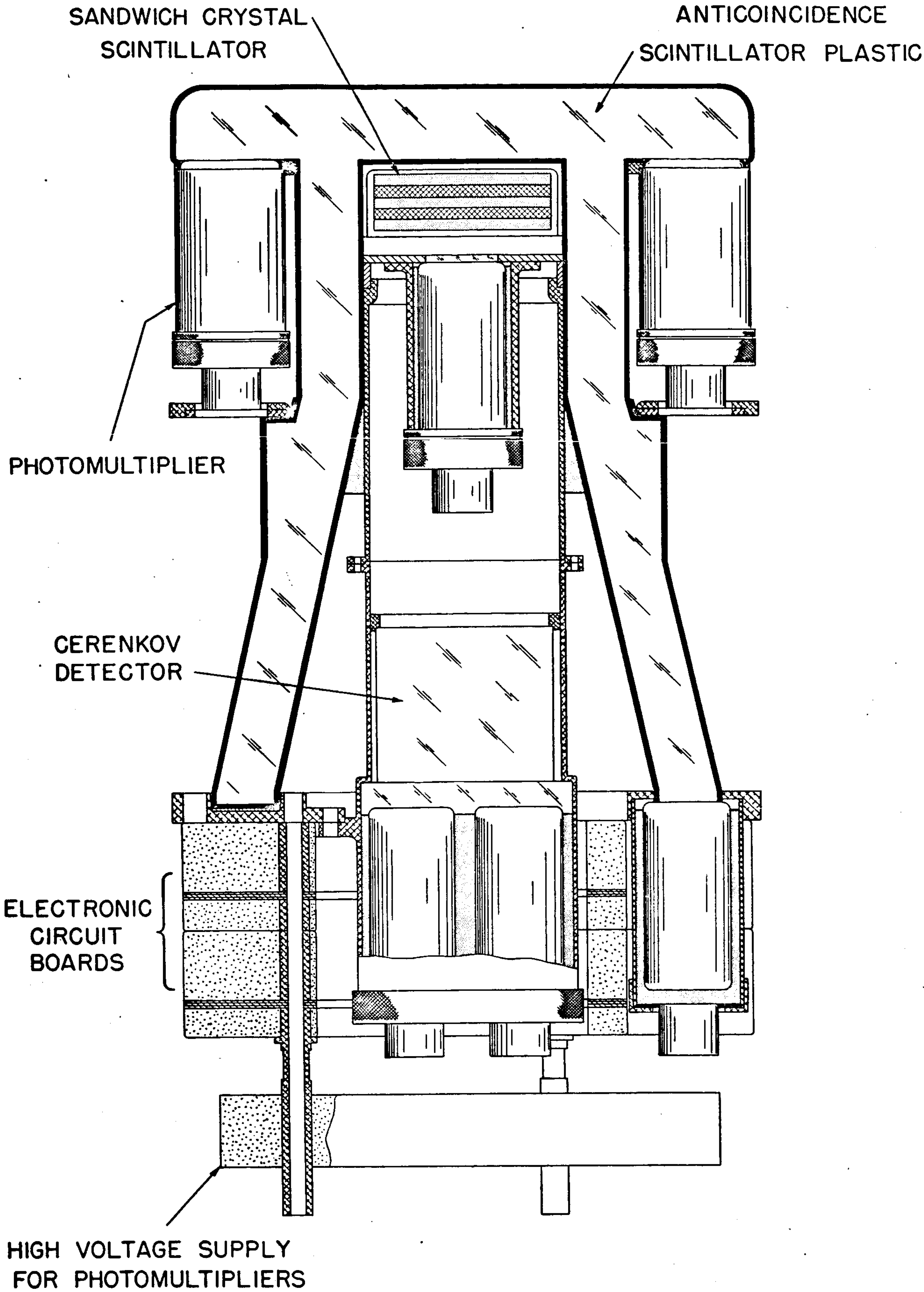


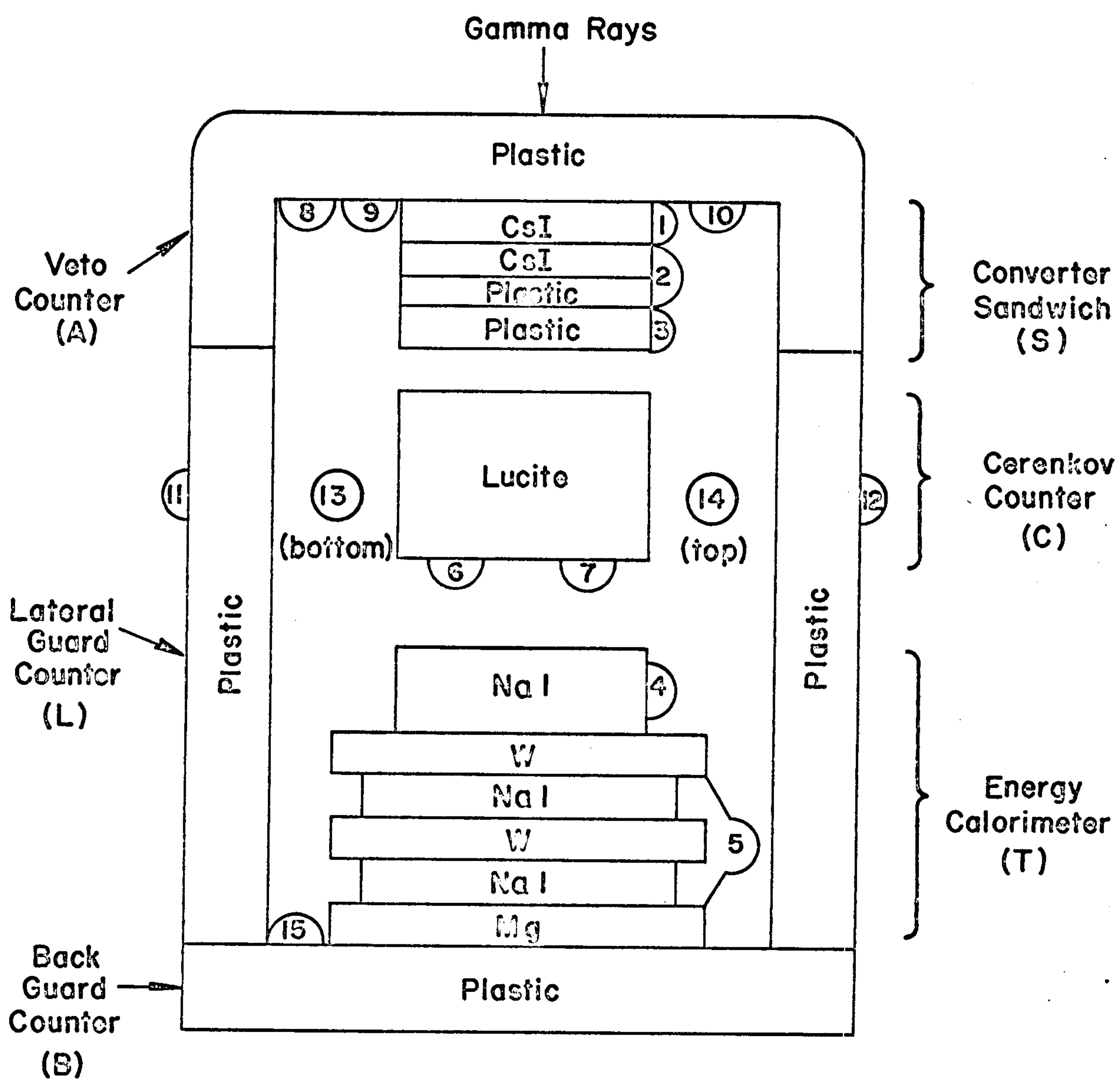
ORNL-DWG 69-2567

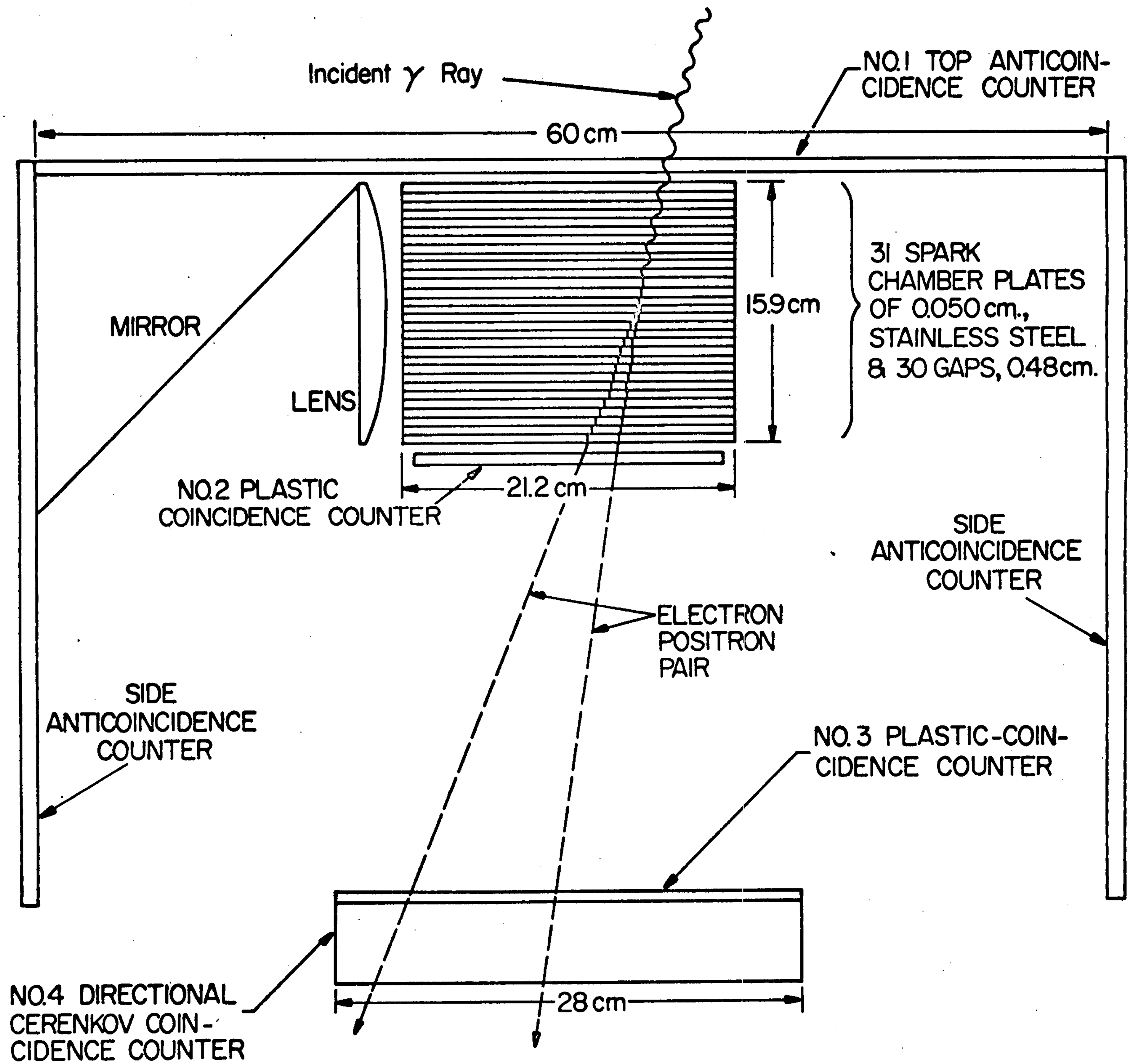


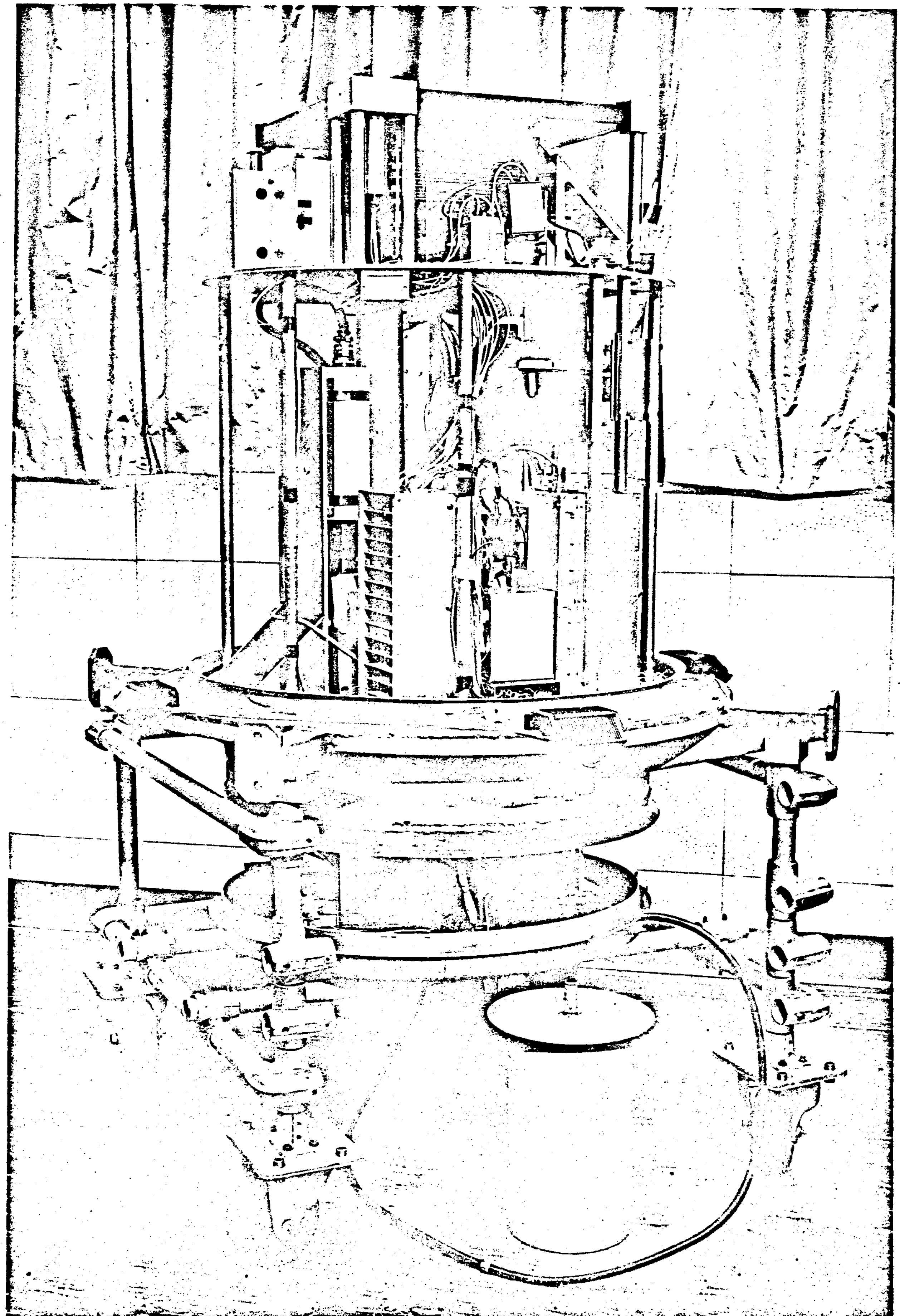


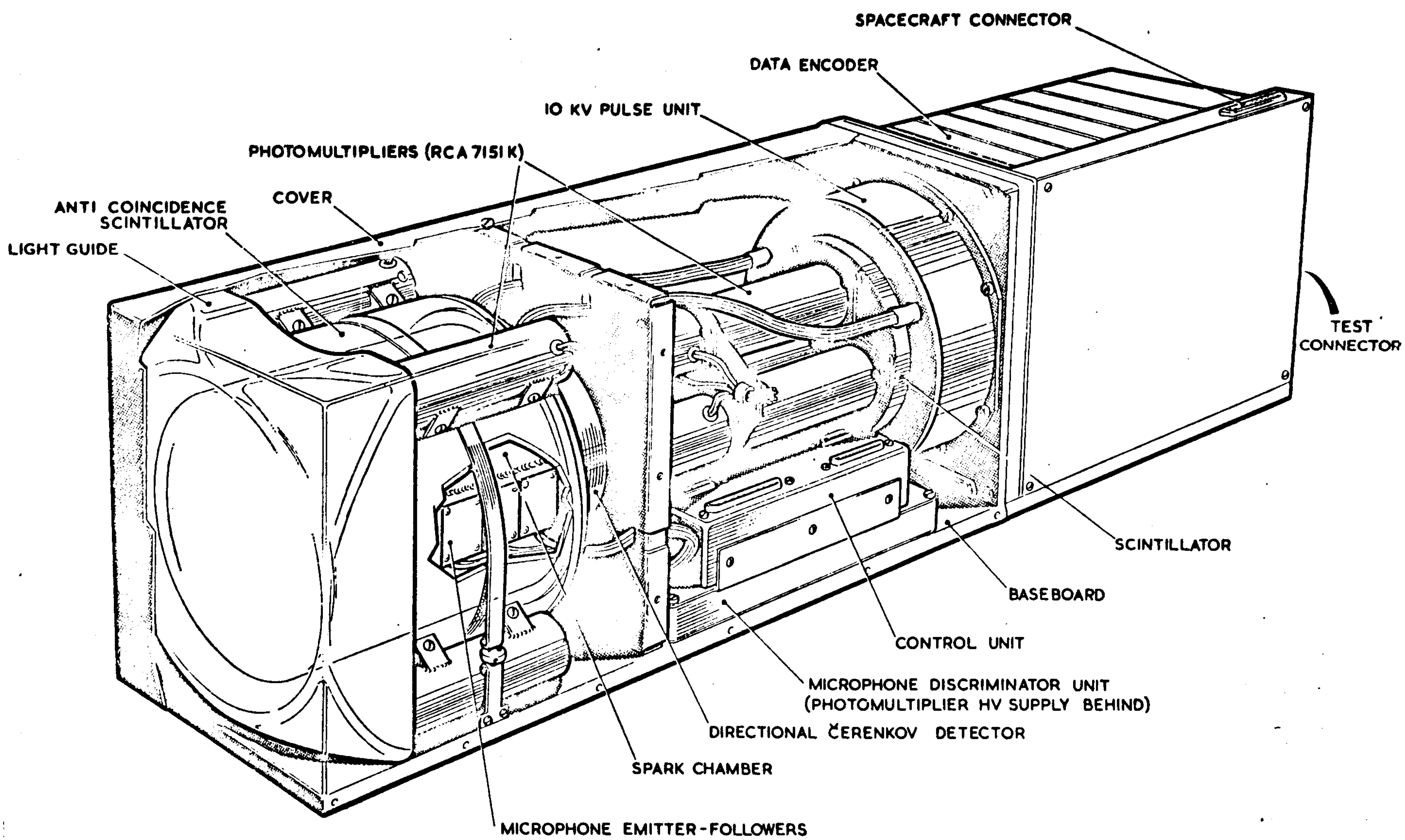
HIGH-ENERGY GAMMA-RAY TELESCOPE

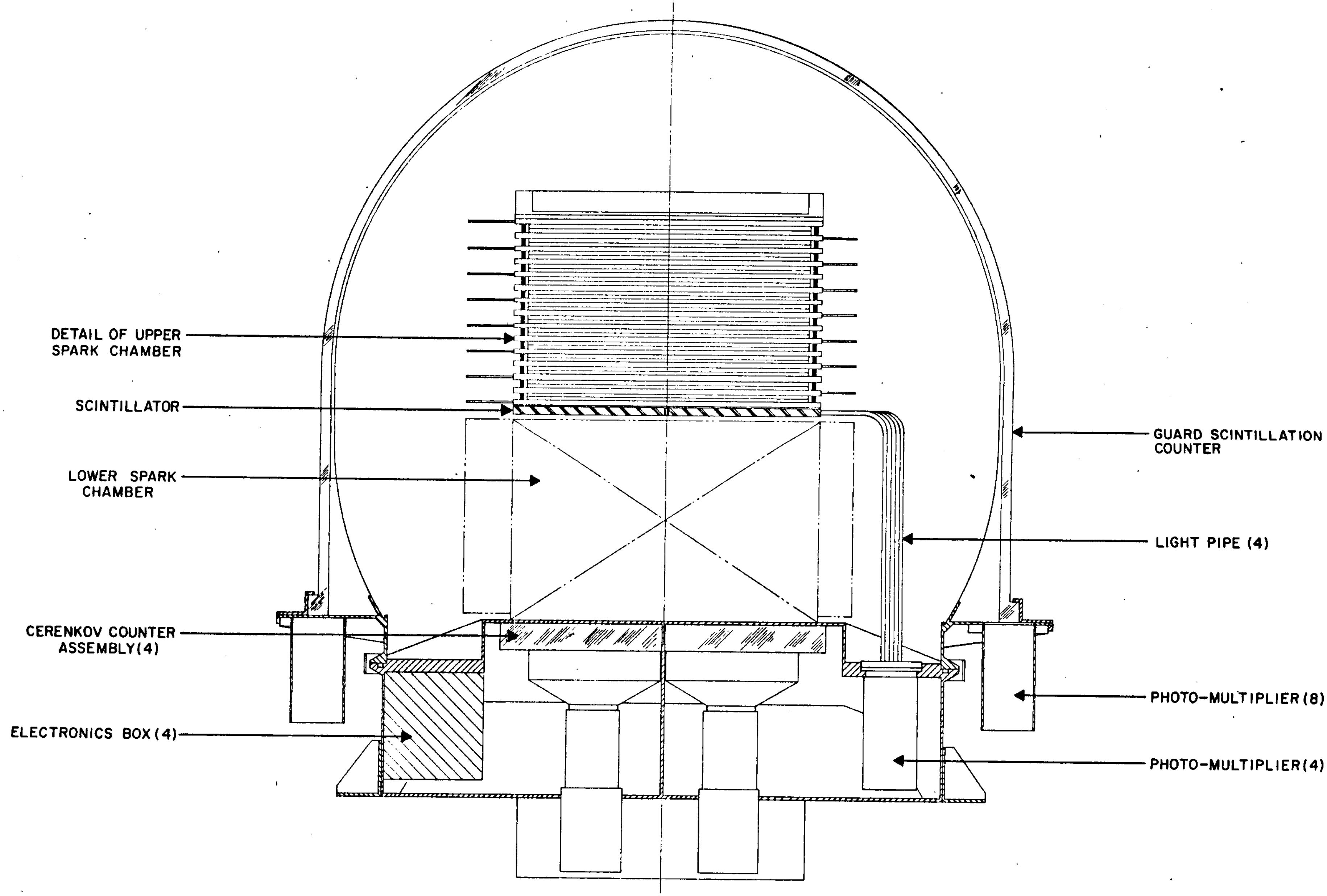

SANDWICH CRYSTAL SCINTILLATOR
ANTICOINCIDENCE SCINTILLATOR PLASTIC
PHOTOMULTIPLIER
CERENKOV DETECTOR
ELECTRONIC CIRCUIT BOARDS
HIGH VOLTAGE SUPPLY FOR PHOTOMULTIPLIERS


Gamma Rays
Plastic
Veto Counter (A)
CsI
CsI
Plastic
Plastic
Converter Sandwich (S)
Lucite
(bottom)
(top)
Cerenkov Counter (C)
Lateral Guard Counter (L)
Plastic
Plastic
Na I
W
Na I
W
Na I
Mg
Energy Calorimeter (T)
Back Guard Counter (B)
Plastic
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15

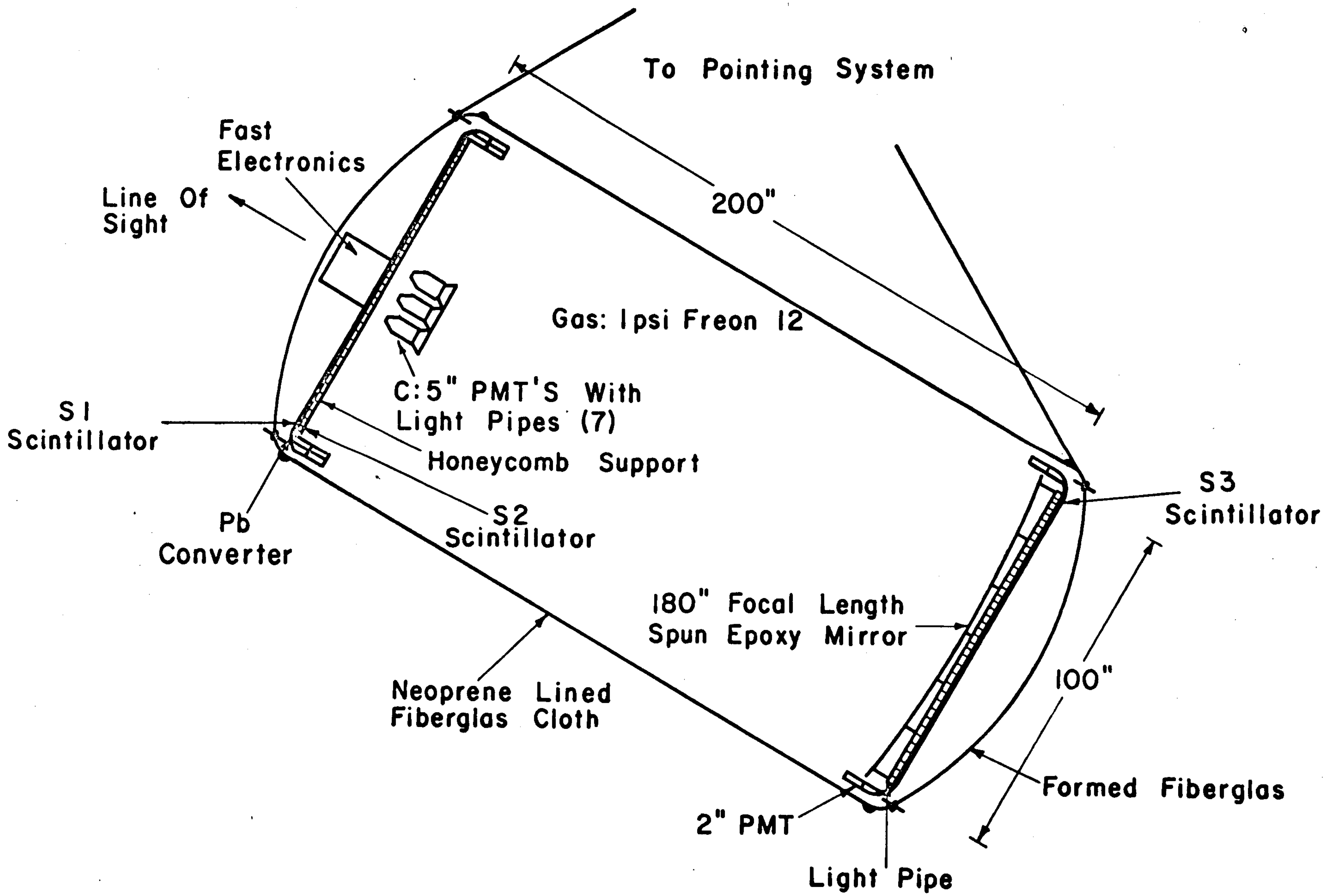

Incident γ Ray
NO.1 TOP ANTICOIN-
CIDENCE COUNTER
60 cm
MIRROR
LENS
15.9 cm
31 SPARK
CHAMBER PLATES
OF 0.050 cm.,
STAINLESS STEEL
& 30 GAPS, 0.48 cm.
NO.2 PLASTIC
COINCIDENCE COUNTER
21.2 cm
SIDE
ANTICOINCIDENCE
COUNTER
ELECTRON
POSITRON
PAIR
SIDE
ANTICOINCIDENCE
COUNTER
NO.3 PLASTIC-COIN-
CIDENCE COUNTER
NO.4 DIRECTIONAL
CERENKOV COIN-
CIDENCE COUNTER
28 cm




SPACECRAFT CONNECTOR
DATA ENCODER
10 KV PULSE UNIT
PHOTOMULTIPLIERS (RCA 7151 K)
COVER
ANTI COINCIDENCE SCINTILLATOR
LIGHT GUIDE
TEST CONNECTOR
SCINTILLATOR
BASEBOARD
CONTROL UNIT
MICROPHONE DISCRIMINATOR UNIT (PHOTOMULTIPLIER HV SUPPLY BEHIND)
DIRECTIONAL ČERENKOV DETECTOR
SPARK CHAMBER
MICROPHONE EMITTER-FOLLOWERS



SAS-B GAMMA RAY EXPERIMENT


To Pointing System
200"
Fast
Electronics
Line Of
Sight
Gas: 1psi Freon 12
C: 5" PMT'S With
Light Pipes (7)
S1
Scintillator
Honeycomb Support
Pb
Converter
S2
Scintillator
S3
Scintillator
180" Focal Length
Spun Epoxy Mirror
100"
Neoprene Lined
Fiberglas Cloth
Formed Fiberglas
2" PMT
Light Pipe